Maryland Department of Natural Resources
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ADMINISTRATIVE REPORT

WATER-SUPPLY POTENTIAL OF THE COASTAL PLAIN AQUIFERS IN CALVERT, CHARLES, AND ST. MARY'S COUNTIES, MARYLAND, WITH EMPHASIS ON THE UPPER PATAPSCO AND LOWER PATAPSCO AQUIFERS

by

David D. Drummond

Prepared in cooperation with the
Boards of County Commissioners of
Calvert, Charles, and St. Mary's Counties
and the
United States Department of Interior
Geological Survey

June, 2005

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CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS—CONTINUED

TABLES

TABLES—CONTINUED

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EXECUTIVE SUMMARY

A study was conducted of the water-supply potential of the aquifer system in Calvert, Charles, and St. Mary's Counties. A ground-water flow model was developed that simulates water levels in the five major aquifers in Southern Maryland. The flow model was calibrated using historical pumpage and water levels, and was then used to estimate future water levels through 2030 based on future pumpage scenarios compiled in conjunction with county planning departments.

Projected water demand in Calvert and St. Mary's Counties through 2030 could be met by increased pumpage in the Aquia aquifer (without shifting withdrawals to deeper aquifers) without reducing water levels below the 80-percent management level. Shifting a portion of public-supply withdrawals from the Aquia aquifer to the Upper Patapsco aquifer would result in an increase in available drawdown in the Aquia aquifer in many areas of the counties, with minimal effects on drawdowns in the outcrop area in Charles County.

In Charles County, the proximity of the major pumping centers to the outcrop/recharge areas of the Patapsco aquifers, and the relatively shallow depth of the aquifers limit their productive capabilities. Withdrawals from the Magothy aquifer in the Waldorf area cannot be increased significantly above 2002 amounts without lowering heads below the 80-percent management level by 2030. Simulated future drawdowns indicate the potential for river-water intrusion into the Upper Patapsco and Lower Patapsco aquifers from the Potomac River in the Indian Head area. Simulated drawdowns also indicate the potential in shallow portions of the Patapsco aquifers for reduced base flow to streams and a lowered water table, which could reduce the amount of water available in some types of wetlands. These issues could not be specifically addressed in the context of a large regional study, but require additional examination. Alternative water-supply options should be evaluated in Charles County, such as utilizing the Patuxent aquifer, or replacing current production well fields with new wells in the Patapsco aquifers farther southeast.

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INTRODUCTION

The water needs of Calvert, Charles, and St. Mary's Counties (referred to in this report as Southern Maryland) are predominantly supplied by five major aquifers. From shallow to deep, these are the Piney Point, Aquia, Magothy, Upper Patapsco, and Lower Patapsco aquifers. Declining water levels and water-quality issues in the Aquia aquifer have prompted water-supply managers to shift a portion of ground-water withdrawals from the Aquia aquifer to the deeper Upper Patapsco and Lower Patapsco aquifers. As of 2002, cones-of-depression have formed in the Aquia aquifer centered at Lexington Park (200 feet [ft] below sea level), the Magothy aquifer at Waldorf (90 ft below sea level), the Upper Patapsco aquifer at La Plata (136 ft below sea level), and the Lower Patapsco aquifer at La Plata (200 ft below sea level). Because of these concerns, a study was undertaken to assess the water-supply potential of these aquifers, and to provide water managers with information necessary for long-term planning.

Purpose and Scope

The purpose of this Administrative Report is to summarize the preliminary conclusions of a 5-year study that focused on the water-supply potential of the five major aquifers in Southern Maryland (fig. 1). Information is included on the hydrogeology, population trends, and the ground-water flow model used to simulate future conditions, in order to provide the background necessary to understand the conclusions. In addition to this Administrative Report, a Basic Data Report is in preparation that will provide data collected from six exploratory test wells drilled into the Patapsco aquifer as a part of this study (fig. 2). A Report of Investigations, currently (2005) in preparation, will present a detailed analysis of the test-well data, the development and deployment of the ground-water flow model, and the hydrogeology and water-supply potential of the aquifer system in Southern Maryland. The Patuxent aquifer, which underlies the Patapsco aquifers throughout the study area and may be utilized in the future as a water supply, is not addressed in this report. Crystalline bedrock, which underlies the Patuxent aquifer, is not considered to be a significant water supply, and is also not addressed in this report.

Acknowledgments

Cooperative funding for this study was provided by the County Commissioners of Calvert, Charles, and St. Mary's Counties; the Maryland Department of Natural Resources; and the U.S. Department of the Interior, Geological Survey. Additional funding was provided by Chesapeake Ranch Estates. Sites for test-well drilling were provided by the Calvert County Department of Public Works, Charles County Public Schools, Chesapeake Ranch Water Company, Maryland Department of Natural Resources, and St. Mary's County Metropolitan Commission.

Field data collection was conducted by Nadine Calis, Karen Jennings, Brandon Fewster, Barbara Cooper, and David Bolton, all of the Maryland Geological Survey. Geographic information system (GIS) support services were provided by Mary Valentino of the Center for Geographic Information Sciences at Towson University. Judith Wheeler

of the U.S. Geological Survey maintained a data base of historical pumpage information in Maryland, and provided pumpage data for flow-model calibration. Stephen Curtin, also of the U.S. Geological Survey, performed geophysical logging of the test wells, and provided historical water-level data for flow-model calibration.

The report was reviewed by Earl Greene of the U.S. Geological Survey; and David Bolton, Emery Cleaves, and Harry Hansen (retired) of the Maryland Geological Survey. Donajean Appel of the Maryland Geological Survey assisted in preparation of the tables and other aspects of the report.

Special thanks go to the homeowners in Calvert, Charles, and St. Mary's Counties who patiently endured round-the-clock test-drilling operations in their neighborhoods.

HYDROGEOLOGY

The Southern Maryland study area (fig. 1) is located entirely within the Atlantic Coastal Plain Province, and is underlain by a wedge-shaped body of sediments, which generally thickens and deepens to the southeast. These sediments include layers of sand, gravel, silt, and clay, and were deposited on a basement surface of crystalline bedrock. The bedrock emerges at land surface along the Fall Line (which approximately follows Interstate 95 in Maryland and Virginia) and is deepest at Point Lookout in southern St. Mary's County. Sand and gravel layers form aquifers, which transmit and produce water to wells, and silt and clay layers form confining units (or aquicludes), which inhibit the movement of ground water.

Aquifer Descriptions

Seven major aquifers underlie the study area, all of which are used for water supply (to varying degrees) in different parts of the study area (fig. 3, tab. 1). From shallowest to deepest, these aquifers are the Surficial (or Water-table), Piney Point, Aquia, Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers. Although in places aquifers are in direct contact with other aquifers, they are generally separated by confining units (fig. 3). Potentiometric surfaces for 2002 are shown in figures 4a through 4e, and hydrographs for major aquifers in each county are shown in figures 5a, 5b and 5c. Each aquifer is described briefly here.

The Surficial aquifer is exposed at the land surface, and receives recharge directly from precipitation. Hydrogeologic processes such as evaporation, transpiration to plants, and base flow to streams occur within the Surficial aquifer. It comprises a variety of geologic materials, and its hydraulic properties are extremely variable. It provides recharge to deeper aquifers, either as leakage through intervening confining units or as direct infiltration where it directly contacts an underlying aquifer. The Surficial aquifer is tapped by irrigation wells and some older farm and domestic wells, but it is not widely used for potable water supply because of its vulnerability to contamination and reduced dependability during droughts.

The Piney Point aquifer, as described in this report, includes sediments of the Piney Point Formation; deeper, sandy units of the Calvert Formation; and the sandy, upper parts of the Nanjemoy Formation. In some publications it is referred to as the Piney Point-Nanjemoy aquifer (Chapelle and Drummond, 1983; Achmad and Hansen, 1997). It is overlain by the Chesapeake confining unit in Calvert and St. Mary's Counties. The

Nanjemoy Formation is exposed at the surface in central Charles County where it is chiefly a silty, clayey, fine sand, but the Piney Point aquifer exists only in the subsurface in Maryland. Although a few major users in southern Calvert and St. Mary's Counties pump from the Piney Point aquifer, it is primarily used for domestic water supply. The Piney Point aquifer is present in eastern Charles County, but is not a major water producer there.

The Aquia aquifer includes sandy sediments of the Aquia Formation in eastern Charles County, all of Calvert County, and most of St. Mary's County. It undergoes a transformation to silty sediments (facies change) in southeastern St. Mary's County where it is not used for water supply. It is generally separated from the overlying Piney Point aquifer by the Marlboro Clay and deeper, clayey parts of the Nanjemoy Formation. The Aquia aquifer is used extensively for domestic and major-user supplies in Southern Maryland, as well as in Virginia and the Eastern Shore of Maryland. It is not used for water supply west of US 301 in Charles County, and subcrops in northwestern Charles County.

A deep cone-of-depression (as much as 200 ft below sea level) has formed in the Aquia aquifer in the Lexington Park/ Solomons area of St. Mary's and Calvert Counties, where it is heavily pumped for public, commercial, and military supplies (fig. 4b). Although water from the Aquia aquifer is generally of good quality, arsenic concentrations, in some places, exceed the new U.S. Environmental Protection Agency Maximum Contaminant Level (MCL) of 10 micrograms per liter (µg/L) (Federal Register, 2001) for public water supplies. Because of these considerations, water-supply managers in Calvert and St. Mary's Counties are seeking to shift some ground-water usage from the Aquia aquifer to the deeper Patapsco aquifers.

The Magothy aquifer underlies the Aquia aquifer, and is separated from it by the Brightseat confining unit. The Magothy aquifer pinches out (thins to zero thickness) in southern Charles County, northern St. Mary's County and northern Calvert County, but is used extensively for domestic and public supplies north of the pinch out. Heavy pumping in the Waldorf area has resulted in a cone-of-depression, which was 90 ft below sea level in 2002 (fig. 4c).

The Upper Patapsco aquifer underlies the Magothy aquifer and is separated from it by clayey units in the top of the Patapsco Formation and bottom of the Magothy Formation, which are referred to collectively as the Upper Patapsco confining unit. The Upper Patapsco aquifer includes sandy beds in the upper part of the Patapsco Formation, which is the upper unit of the Potomac Group. The Upper Patapsco aquifer is not a continuous sand body; rather, it comprises complexly stratified sandy units separated locally by silty and clayey units. Individual sand units of the Upper Patapsco aquifer are impossible to delineate with the data currently available; however, they appear to be sufficiently interconnected at the regional scale to form a single aquifer.

The Upper Patapsco aquifer extends to the northeast through Prince George's and Anne Arundel Counties, and beneath the Chesapeake Bay to the Eastern Shore of Maryland. It probably extends to the southwest across the Potomac River, but the Potomac Group is not subdivided into the Upper Patapsco, Lower Patapsco, and Patuxent aquifers in Virginia as it is in Maryland. The bluffs along the Potomac River in northwestern Charles County contain outcrops of the upper part of the Potomac Group, and the Upper Patapsco aquifer outcrops and subcrops in this area. It also subcrops beneath the Potomac River, and river-water intrusion has occurred in the Indian Head area from the tidal part of the river (Hiortdahl, 1997).

The Upper Patapsco aquifer is used extensively for public supply in central Charles County, where a cone-of-depression has formed as much as 136 ft below sea level (fig. 4d). This cone-of-depression extends northwest to the Potomac River, where it may induce dewatering of the aquifer and river-water intrusion. The Upper Patapsco aquifer is also pumped heavily by major users in Prince George's and Anne Arundel Counties to the north of the study area, and by domestic users in Charles County. A few major users pump the Upper Patapsco aquifer in Calvert and St. Mary's Counties, and it is used on the Eastern Shore of Maryland as far south as Crisfield, in Somerset County.

The Lower Patapsco aquifer underlies the Upper Patapsco aquifer, and is separated from it by clayey units in the middle part of the Patapsco Formation, referred to as the Middle Patapsco confining unit. The Lower Patapsco aquifer comprises sandy units in the lower part of the Patapsco Formation. Like the Upper Patapsco aquifer, the Lower Patapsco aquifer is composed of numerous sandy beds, which may be hydraulically separated locally, but coalesce on a regional scale to form a single aquifer.

Potomac Group sediments extend to the southwest of the study area into Virginia, but correlation to aquifers from Maryland is uncertain. The Lower Patapsco aquifer also extends northeast to northern Anne Arundel County, but correlation across southern Prince George's County, where data are scarce, is also uncertain. It extends across the Chesapeake Bay to Queen Anne's and Kent Counties on the Eastern Shore of Maryland, but its hydraulic character on the lower Eastern Shore is uncertain.

The Lower Patapsco aquifer is pumped heavily by major users in central and northwestern Charles County, but is not currently used in Calvert or St. Mary's Counties. A cone-of-depression nearly 200 ft below sea level has formed in the Waldorf/La Plata area (fig. 4e). This cone-of-depression extends northwest to the Potomac River, and may continue beneath the Potomac River into Fairfax and Prince William Counties in Virginia.

The Patuxent aquifer underlies the Lower Patapsco aquifer, and is separated from it by the Arundel confining unit. The Patuxent aquifer is the deepest Coastal Plain aquifer in Maryland, and rests on the bedrock surface. It is pumped by a few wells in northwestern Charles County, but is not used elsewhere in the study area, where sparse data are available. Although the Patuxent aquifer is a possible water source throughout the study area, its potential for development is limited because of its great depth, undetermined hydraulic characteristics, and the presence of brackish water in places, for instance at Lexington Park (Hansen and Wilson, 1984). Thick, dense clays and silts of the Arundel confining unit separate the Patuxent aquifer from overlying aquifers, and probably do not allow much leakage. The Patuxent aquifer is not addressed further in this report. Bedrock underlies the Patuxent aquifer, and is not considered a potential source of water.

Test Wells

Six deep test wells were drilled in cooperation with the U.S. Geological Survey as a part of this study to obtain hydrogeologic information on the Upper and Lower Patapsco aquifers in Southern Maryland. Well-construction information is summarized in table 2. Two wells were drilled in each county; four were screened in the Lower Patapsco aquifer, and two were screened in the Upper Patapsco aquifer (fig. 2). Each well was drilled to about 1,650 ft, and sediment samples were collected at 10-foot or 20-foot intervals to describe lithologies and to investigate the age and depositional environment of the sediments using microfossils. Geophysical logging (gamma-radiation, spontaneous potential, single-point resistance, and multi-point resistivity) was conducted on the uncased boreholes, and screen depths were chosen based primarily on geophysical logs.

An aquifer test, consisting of a 24-hour pumping phase and 24-hour recovery phase, was conducted to determine transmissivity and specific capacity for each well. Water samples were obtained near the end of each pumping interval for chemical analysis. Continuous water-level recorders were installed on all wells to determine short-term fluctuations and long-term trends. After obtaining a few years of water-level data, the recorders will be removed and periodic measurements will be taken to document future water-level trends.

Water-Level Trends

Water levels have declined significantly since the 1970's in all five major aquifers in the study area (figs. 5a-c). The declines are caused by steadily increasing ground-water withdrawals as population has increased. An exception is the Piney Point aquifer near Lexington Park (fig. 5c), where water levels reached a low of about 33 ft below sea level in the late 1980's, then recovered to about 20 ft below sea level. This recovery is caused by a reduction in public-supply withdrawals in the Lexington Park area. The water level in well CA Fd 51 near Calvert Cliffs declined steadily from about 10 ft above sea level in 1980 to about 1 ft below sea level in 2000. Since then it has remained about the same.

In the Aquia aquifer, water levels have declined by about 100 ft at Solomons in Calvert County (well CA Gd 6, fig. 5a) and by 65 ft and 90 ft at Leonardtown (well SM Dd 50) and Lexington Park (well SM Df 71), respectively, in St. Mary's County (fig. 5c). These are all areas where the Aquia aquifer is heavily pumped for public supplies and other uses.

Water levels have declined in the Magothy aquifer in Calvert and Charles Counties, where it is used extensively for public, domestic, and commercial supplies. The Magothy aquifer is present only in the northern-most part of St. Mary's County, and is not used extensively there. The water level steadily declined by about 45 ft from 1975 until present (well CA Dc 35, fig. 5a) at Scientists Cliffs in Calvert County. The water level declined by about 90 ft from 1975 until present (well CH Bf 134, fig. 5b) at Waldorf in Charles County.

Water levels in the Upper Patapsco aquifer have declined steadily in all three counties, even though it is used extensively only in Charles County. The water level declined by about 32 ft at Randle Cliff (well CA Cc 55, fig. 5a) in northern Calvert County from 1975 until present. The water level declined by about 37 ft at Lexington Park (well SM Df 84, fig. 5c) in St. Mary's County from 1983 until present. In the La Plata area of Charles County, the water level has declined by almost 100 ft from 1969 until present (well CH Cd 43, fig. 5b).

In Charles County, water levels in the Lower Patapsco aquifer have declined about 50 ft at St. Charles (well CH Be 58, fig. 5b) from 1986 until present, and about 145 ft at Potomac Heights (well CH Bc 24, fig. 5b) near Indian Head from 1988 until present. The Lower Patapsco aquifer is used extensively in central and northwestern Charles County, but not elsewhere in the study area. No long-term water-level records are available in Calvert or St. Mary's Counties, but measurements for the last several years from test wells drilled during this project show declines of about one ft per year.

WATER-MANAGEMENT CRITERIA

In this report, the primary criterion for determining the productive capabilities of the confined aquifers in Southern Maryland is the 80-percent management level. This level is calculated at a given location as 80 percent of total available drawdown, measured from the prepumping water level to the top of the aquifer. Maryland Department of the Environment (MDE) regulates ground-water users to prevent the regional potentiometric surface from declining below this level. A new user (or existing user applying to increase its withdrawal) would not be granted a permit if the proposed withdrawal rate is predicted to cause the regional head to fall below the management level. This regulation is intended primarily to prevent the partial dewatering of an aquifer near large ground-water users. The 80-percent management level is not applied in or near the shallow unconfined portions of an aquifer because the regional head is below the top of the aquifer even without the influence of pumping.

Results of future model simulations were evaluated by comparing simulated heads with management levels at critical locations. If the simulated regional head falls below the 80-percent management level at a critical location, the pumpage that caused the exceedence is considered excessive. Critical locations were selected where drawdowns are most likely to exceed management levels, or where future pumpage scenarios may cause significant additional drawdown. The flow model calculates average head values for model cells, which are ½-mile square. Heads will be deeper near heavily pumping wells than model-calculated cell averages. Model-calculated heads near pumping centers are somewhat dependent on grid spacing; a model with smaller grid cells would average heads over a smaller area than a model with larger cells, and would simulate heads at pumping wells more accurately. For the purpose of this evaluation, head averaged over an area of 1/4 square mile was considered to represent "regional heads" and was compared with the 80-percent management level. Trescott and others (1976) present a method for calculating the effective radius from a hypothetical well (i.e., the distance from the well at which the model-calculated cell head applies). Applying their equation 12, $r_e = r_1/4.81$ (where r_e is the effective radius and r_1 is the cell width) yields an effective radius for this flow model of 549 ft. This calculation indicates that the model-calculated head would apply at a distance of 549 ft from a production well.

Excessive drawdowns may create other undesirable effects that should be taken into consideration, but are difficult to evaluate on a regional basis. In some areas, wells have been constructed with 4-inch diameter casing near the land surface to accommodate a submersible pump, but reduce to 2-inch diameter below that to save on construction costs; these are referred to as "telescoping wells." If the water level falls below the reduction point in such a well, the pump cannot be lowered further, and the well must be replaced. This is not a problem with the ground-water resource, but may cause significant economic impact in areas where telescoping wells are common.

Although the water table (potentiometric surface in the Surficial aquifer) generally remains constant despite head declines in deeper confined aquifers, it is possible, through cumulative regional withdrawals, to lower the water table at some locations. The consequences of a lowered water table may include reduced base flow to streams (Achmad, 1991), a decrease in water available for plant transpiration, and altered ecology of wetlands. These processes are complex and localized, and cannot be adequately addressed in a regional study of this scope.

Land subsidence may be caused by large head declines if sediments are compressed due to loss of hydrostatic pressure. Possible consequences of land subsidence include lowered land-surface elevation, encroachment of bay water, and an irreversible decrease in porosity and permeability of hydrogeologic units. Land subsidence has not been documented in Maryland, but it is a possibility near the deep cones-of-depression in Charles and St. Mary's Counties.

Potentiometric heads reduced below sea level in shallow aquifers may induce brackish-water intrusion near tidal estuaries or river-water intrusion near non-tidal rivers. River-water intrusion has been documented in the Lower Patapsco aquifer in the Indian Head area of northwestern Charles County, along the Potomac River (Hiortdahl, 1997). Heads have already declined below sea level in this area in the Upper Patapsco and Lower Patapsco aquifers, and increased future withdrawals will lower heads further. Both of these aquifers are unconfined or semi-confined in this area, and river-water intrusion is a possibility. Brackish-water intrusion has been documented in the Aquia aquifer in Anne Arundel County near the Chesapeake Bay (Fleck and Andreasen, 1996), Baltimore Harbor (Chapelle, 1985), and Kent Island (Drummond, 1988). More detailed studies are required to determine the extent and potential for brackish-water or river-water intrusion near the tidal rivers of Southern Maryland.

POPULATION TRENDS

The population of the three Southern Maryland counties increased from 64,626 in 1950 to 281,320 in 2000 (tab. 3) (U.S. Census Bureau, 1995; U.S. Census Bureau, 2003). Charles County experienced the most growth, its population increasing by 97,131, or 415 percent during that time period. Calvert County's population increased by 62,463, or 516 percent, and St. Mary's County's population increased by 57,100, or 196 percent. Figure 6 shows historical and projected population for the three counties from 1900 through 2030.

Population data were used to estimate domestic pumpage for the historical model calibration periods of 1952, 1982, 1994, and 2002. Table 3 shows intercensal population estimates for 1982 (U.S. Census Bureau, 1992) and 1994 (U.S. Census Bureau, 2000) and the interpolated 1952 population that were used for domestic pumpage calculations. Table 3 also shows the estimated population (U.S. Census Bureau, 2003) for July 1, 2002, which was used for domestic pumpage calculations for 2002, and as a base figure for future pumpage projections.

Population projections were used to estimate future domestic and public-supply pumpage. Population projections for 2010, 2020, and 2030, broken down by election district, were obtained from each of the county planning departments (written communication, 2004, Calvert County Department of Planning and Zoning, Charles County Department of Planning and Growth Management, St. Mary's County Department of Land Use and Growth Management). Increases over 2002 populations were used to estimate domestic pumpage and public-supply pumpage for those years. Calvert County changed the boundaries of its election districts in 2002; the old election districts are used throughout this report.

Table 4 shows 2000 population figures from the Census Bureau for each election district in Calvert, Charles, and St. Mary's Counties. Population distribution among election districts was used to estimate domestic-pumpage distribution for historical and future flow-model simulations. Census Bureau population estimates for 2002 were not subdivided by election district, so the percentage increase from 2000 to 2002 for each county was multiplied by the election-district populations of 2000 to obtain estimates of election-district populations for 2002. Table 4 also shows the projected populations for each election district, and the fractional increases over 2002 populations for 2010, 2020, and 2030. Fractional increases from 2002 to 2030 range from 1.10 in Charles County Election District 10 to 2.04 in Charles County Election District 9 (increases of 10 percent to 104 percent). County populations increase by 24 percent, 59 percent, and 42 percent for Calvert, Charles, and St. Mary's Counties, respectively, from 2002 to 2030.

PUMPAGE TRENDS

Ground-water pumpage is an important input parameter to the flow model for historical calibration of the model and for simulating future water levels in response to projected pumpage amounts. Pumpage is broadly divided into two categories: domestic pumpage, which is withdrawn from individual homeowners' wells for household supplies; and major-user pumpage, which is withdrawn from production wells for public-supply, commercial, military, and industrial users.

Major users (those users pumping an average of 10,000 gallons per day (gpd) or more) are regulated by MDE, are required to obtain Ground-water Appropriation Permits (GAPs), and submit reports of monthly pumpage amounts to MDE. Pumpage data collected by MDE are acquired by the U.S. Geological Survey and maintained in a statewide database, which also stores user locations and aquifer assignments. These data were used to construct model-input data sets for the simulation periods 1952, 1982, 1994, and 2002. In some cases, pumpage figures were corrected, based on discussions with water-supply operators. Total major-user pumpage for each county for each historical stress period is shown in table 5.

Future public-supply pumpage was estimated using population projections for 2010, 2020, and 2030. The fractional increase of population from the 2002 population for each election district was multiplied by 2002 pumpage amounts for public-supply users within the relevant district. Pumpage amounts for major users that were not listed as public supply in 2002 were not increased in the future simulations. Although non-public supply water use will probably increase in the future, it is difficult to predict where and when increases will occur because they are not directly related to population increases. Water use outside of the study area was also kept at 2002 levels for future simulations. Total major-user pumpage for each county for each future stress period is shown in table 6.

Domestic pumpage is not regulated or tracked by MDE, so the distribution and amounts were estimated from well records and population figures. Well drillers in Maryland are required to obtain a permit prior to drilling a well, and submit a completion report after drilling a well. The information from these documents is maintained by MDE in a database, which includes well location, depth drilled, screen settings, and yield characteristics. This information was used to estimate the number of domestic wells in each aquifer in each election district in the three Southern Maryland counties in 2002. The number of wells, corrected to census data, was then used to estimate domestic pumpage distribution for each county (tab. 6). Pumpage for each domestic well was estimated to be 162 gpd by multiplying average per capita water use (60 gpd [Andreasen, 2002]) by the average household size of 2.7 for the region.

Historical domestic pumpage for model calibration periods was estimated using county population estimates (tab. 3) and the 2002 pumpage distribution. The fraction of 2002 population for 1952, 1984, and 1992 was multiplied by 2002 pumpage amounts to obtain domestic pumpage amounts for each of those years. The distribution of pumpage, spatially and between aquifers, was assumed to be the same as in 2002.

Future domestic pumpage was estimated in a similar way. The fractional population increase for each election district (tab. 4) was multiplied by the 2002 domestic pumpage distribution to obtain domestic pumpage estimates for 2010, 2020, and 2030. As with historical pumpage estimates, the distribution of pumpage spatially and between aquifers was assumed to be the same as in 2002. Total projected pumpage amounts for each county are shown in table 6 as Simulation 1.

FLOW-MODEL SIMULATIONS

A ground-water flow model was developed to simulate flow and heads in the major aquifers used in the Southern Maryland area. Visual Modflow version 2.8.2 (Waterloo Hydrogeologic) was used for all simulations. The hydrogeologic, layered structure of aquifers and confining units was entered into the model, hydraulic characteristics were assigned to the layers, and boundary conditions were entered at the edges of the model (fig. 7). The model was then calibrated, using prepumping and historical pumping conditions, by matching simulated heads with measured heads. The calibrated model was then used to simulate future ground-water heads in response to various pumping scenarios. A description of the flow-model setup is provided in the appendix. Estimates of future ground-water pumpage were entered into the model for stress periods ending in 2010, 2020, and 2030 (tab. 6a-c). Flow and heads were simulated at the end of each stress period, and heads at critical locations were compared with the 80-percent management level.

Critical locations for head comparison were chosen where heads are most likely to exceed the 80-percent management level in future simulations. These locations are shown in figure 8, and information for the locations is shown in table 7. Critical locations include the centers of major cones-of-depression, hypothetical new production wells, and one area in northern Calvert County where numerous domestic wells in the Aquia aquifer have reduced the potentiometric surface without forming a typical cone-of-depression. Where drawdown exceeds the management criteria (heads are below the 80-percent management level) the water user would be in violation of MDE regulations, and alternative pumpage distributions should be sought. Table 7 shows simulated heads and remaining available drawdown for each scenario for 2030, and the management level at each location. Where simulated drawdown exceeds the management level (remaining available drawdown is negative), the value is highlighted in light gray, and where it exceeds the top of the aquifer it is highlighted in dark gray. In addition, table 7 shows the simulated prepumping heads and the altitudes of the top of the aquifer used to calculate management levels. MDE prohibits the placement of a well pump below the top of the aquifer in which the well is screened, which prevents water levels from actually falling below the top of the aquifer.

Future Pumpage Scenarios

Estimates of future pumpage were derived from population projections, planned areas of growth, and hypothetical new users. A series of eight major pumpage scenarios was developed that incorporates increases in population, and brackets the possible extremes of future pumpage conditions. Hypothetical new pumping centers were added in some scenarios to evaluate the impact of additional major withdrawals. All pumpage scenarios were simulated with the calibrated flow model, and the results were evaluated in terms of the 80-percent management level at critical locations in the study area.

All scenarios simulate the time period 2003 through 2030. Pumpage was entered for an 8-year period, 2003 to 2010, and two 10-year periods, 2011 to 2020, and 2021 to 2030. Pumpage was held constant during each of these stress periods, and heads are tabulated for the end of each period.

Pumpage was increased for future scenarios only for domestic and public-supply wells within the study area (see appendix). Other major users within the study area and all users outside the study area were held at 2002 withdrawal rates, which may cause underestimates of drawdown in future simulations. In addition, the general-head boundaries at the lateral edges of the model, which approximate pumpage outside the model area, were also held at 2002 head conditions. Underestimates would probably be greatest near areas of adjacent counties that are likely to experience high growth rates in the next several decades. Scenario 2 provides an indication of the magnitude of additional drawdown that may result from underestimates of future pumpage by increasing all withdrawal rates in the study area by 10 percent (Scenario 2a) and 20 percent (Scenario 2b).

The first simulation (Scenario 1) represents "base conditions," and simulates the most likely set of conditions without shifting pumpage to deeper aquifers. Each subsequent simulation is a variation of the base conditions, and changes a single aspect of future conditions. The results of the subsequent simulations can be compared to the results of Simulation 1 to provide an evaluation of the range of possible future conditions.

In addition to the eight major pumping scenarios, a preliminary simulation was run in which 2002 pumpage was continued unchanged from 2003 through 2030. This simulation indicates the future residual drawdown that would occur even if pumpage were not increased above 2002 levels. It is referred to as Scenario 0 in Table 7.

In this report, results for Scenarios 1, 2 and 5 are discussed in detail. Figures 9a through 9e show potentiometric surfaces for Scenario 1 for each aquifer. Figures 10 through 12 show drawdown maps for all five aquifers. Results for all simulations are summarized in table 7, and will be discussed in detail in the Report of Investigations (in preparation).

Scenario 1

Scenario 1 represents pumpage increases to accommodate projected population increases through 2030 without making major changes to the water-production infrastructure. Pumpage at domestic "delegate" wells (an explanation of delegate wells is provided in the appendix) and public-supply production wells was increased according to population projections for each county election district. Pumpage at all other major users (commercial, agricultural, and military) within the study area and all pumpage outside the study area was held constant at 2002 rates. Boundary conditions at the top of the model (constant head for the water-table aquifer and estuaries) and sides of the model (general-head at the lateral boundaries) also were held at 2002 levels.

Results of Scenario 1 for 2030 are shown in figures 9 and 10, and summarized in table 7. Figures 9a through 9e show the simulated potentiometric surfaces of the five major aquifers in Southern Maryland based on the conditions outlined for Scenario 1, and Figures 10a through 10e show drawdowns for the simulation period 2003 to 2030. Heads in the Piney Point aquifer decline as much as about 60 ft below sea level in central St. Mary's County and 80 ft below sea level near Prince Frederick in Calvert County, primarily due to increases in domestic pumpage in those areas (fig. 9a). Drawdowns are as much as about 20 ft in central St. Mary's County and 30 ft in central Calvert County. About 74 ft of drawdown is still available at Town Creek (critical location 26).

In the Aquia aquifer, the cone-of-depression centered at Lexington Park (critical location 19) has deepened to almost 250 ft below sea level, which is about 60 ft deeper than in 2002. About 109 to 117 ft of available drawdown remains as of 2030 at the center of the cone-of-depression there. At Prince Frederick (critical location 3), head has declined to about 120 ft below sea level, with 141 ft of remaining available drawdown. In eastern Charles County and northern St. Mary's County, heads in the Aquia aquifer have declined to 100 ft below sea level, due to increased domestic pumpage and leakage to the underlying Magothy aquifer.

In the Magothy aquifer, head has declined to as much as 215 ft below sea level in the Waldorf area (critical location 12) by 2030. This drawdown exceeds the 80-percent management level by nearly 40 ft (tab. 7). This drawdown is caused by a population increase of nearly 100 percent in central Charles County (tab. 4) and corresponding increase in public-supply pumpage. It should be noted that MDE has imposed a cap of 2.87 million gallons per day on ground-water withdrawals from the Magothy aquifer in the Waldorf area, and would not allow the increases simulated in this scenario.

A drawdown of 80 ft has reduced heads in the Upper Patapsco aquifer to about 195 ft below sea level in the cone-of-depression centered near La Plata (critical location 10). This leaves only about 9 ft of remaining available drawdown at this site. A small cone-of-depression has formed in the Lexington Park area (critical location 27) in the Upper Patapsco aquifer, which is 81 ft below sea level by 2030, caused by increased pumpage at the Lexington Park water system. The cone-of-depression centered at Waldorf reaches southeast to the Lexington Park area, and causes some drawdown there. The management level is about 450 ft below sea level at Lexington Park, so there is still 370 ft of available drawdown in 2030. The cone-of-depression centered at Waldorf also extends northwest to the Potomac River and the outcrop/recharge area of the Upper Patapsco aquifer. This may produce undesirable consequences such as a declining water table and river-water intrusion.

In the Lower Patapsco aquifer, increased public-supply withdrawals in central Charles County have caused drawdowns of 140 ft by 2030 in the cone-of-depression in the Waldorf-La Plata area (critical location 14). Heads have declined to 315 below sea level at the deepest part of the cone, although 281 ft of available drawdown remain there in 2030 (figs. 9e, 10e, tab. 7). Farther northwest in the Indian Head area (critical location 13), heads have declined to 166 ft below sea level, which is 37 ft below the management level, and at the top of the aquifer. However, simulated heads are probably too deep here because simulated withdrawals from the military base at Indian Head are concentrated at one well, whereas in reality they are distributed among several wells. The simulated cone-of-depression in the Lower Patapsco aquifer extends northwest beyond the Potomac

River to the outcrop/recharge area of the aquifer. As in the Upper Patapsco aquifer, this may produce undesirable consequences such as a declining water table and river-water intrusion.

Scenario 2

Scenario 2 represents additional increases of pumpage within the study area to account for underestimates in withdrawal rates. Scenario 2a increases all pumpage within the study area by 10 percent over pumpage in Scenario 1, and Scenario 2b increases pumpage by 20 percent over pumpage in Scenario 1.

Results for Scenario 2 are similar to Scenario 1, but drawdowns are greater in all five aquifers. Drawdowns for 2002 to 2030 for Scenario 2b (20-percent increase in pumpage over Scenario 1) are greater than 40 ft in the Piney Point aquifer at Lexington Park (fig. 11a), and 100 ft in the Aquia aquifer at Lexington Park and central Charles County (fig. 11b). Management levels are not exceeded in either of these aquifers for this scenario, although only 42 ft of available drawdown remains at Charlotte Hall in the Aquia aquifer (critical location 23). In the Magothy aquifer, drawdown for 2002 to 2030 is greater than 160 ft at Waldorf (critical location 12), and the management level is exceeded by over 90 ft (fig. 11c). Water levels are below the top of the Magothy aquifer in this simulation (tab. 7). In the Upper Patapsco aquifer, drawdown is greater than 100 ft in the La Plata area (critical location 10), and the management level is exceeded by 30 ft. The management level is exceeded by 10 ft when pumpage is increased by 10 percent in Scenario 2a (tab. 7c). In the Lower Patapsco aquifer, drawdown for 2002 to 2030 is greater than 200 ft in the Waldorf-La Plata area, and remaining available drawdown at Bensville is 77 ft. The management level at Indian Head is exceeded by 72 ft, and the water level is below the top of the Lower Patapsco aquifer there.

Scenario 3

Scenario 3 represents decreases of pumpage within the study area to account for overestimates in withdrawal rates. Scenario 3a decreases pumpage within the study area by 10 percent from pumpage in Scenario 1, and Scenario 3b decreases pumpage by 20 percent from pumpage in Scenario 1.

In Scenario 3, heads in all five aquifers are shallower than in Scenario 1. In Scenario 3a (10-percent decrease in projected pumpage), drawdown exceeds the management level by 20 ft in the Lower Patapsco aquifer at Indian Head, and by 12 ft in the Magothy aquifer at Waldorf. In Scenario 3b (20-percent decrease in projected pumpage), drawdown exceeds the management level only at Indian Head, and only by 2 ft.

Scenario 4

Scenario 4 has all major users pumping at their average GAP rates. The "average GAP rate" is the greatest pumping rate, averaged over an entire year, allowed on the permit as regulated by MDE. The "average GAP rate" is generally lower than the "maximum GAP rate," which is the maximum rate allowable for the month of greatest withdrawal. Although the average GAP rate is greater than 2002 pumpage for most users, the average GAP rate is exceeded by many users in some future scenarios. This indicates that GAP rates would have to be increased to accommodate future population growth.

In Scenario 4, heads are shallower at most locations than in Scenario 1 because the average GAP withdrawal amounts are generally less than necessary to accommodate future population projections. Drawdown at Indian Head exceeds the management level by 87 ft and the head is below the top of the Lower Patapsco aquifer.

Scenario 5

Scenario 5 represents a shift of pumpage in public-supply wells from shallower aquifers to deeper aquifers in order to reduce the decline of water levels in the shallower aquifers near major population centers. This shift would also help reduce reliance on the Aquia aquifer in locations where arsenic concentrations exceed the new MCL of 10 µg/L. Scenario 5a represents a 25-percent shift of public-supply pumpage from the Aquia aquifer to the Upper Patapsco aquifer in Calvert and St. Mary's Counties, and a 25-percent shift of public-supply pumpage from the Magothy aquifer to the Lower Patapsco aquifer in Charles County. Pumpage for other major users in the study area, and domestic pumpage is the same as in Scenario 1, as these users are not likely to incur the expense of constructing new, deeper wells. Scenario 5b represents a shift of 50-percent of public-supply pumpage from the Aquia aquifer to the Upper Patapsco aquifer in Calvert and St. Mary's Counties, and a 25-percent shift of public-supply pumpage from the Magothy aquifer to the Lower Patapsco aquifer in Charles County.

In Scenario 5b, drawdown for 2002 to 2030 in the Piney Point aquifer is only about 20 ft in Calvert County, and near zero elsewhere (fig. 12a). Drawdown for 2002 to 2030 in the Aquia aquifer is about 30 ft in northern St. Mary's County, but heads have recovered (negative drawdown) by about 10 ft in the Lexington Park and Solomons area (fig. 12b). In the Magothy aquifer, drawdown for 2002 to 2030 is only about 20 ft in northern St. Mary's and Charles Counties. Drawdown does not exceed the management level in 2030, but only 65 ft of available drawdown remains at Waldorf. In the Upper Patapsco aquifer, drawdown for 2002 to 2030 is 120 ft in the Waldorf-La Plata area, and the management level is exceeded by about 15 ft at La Plata. A cone-of-depression has formed in the Lexington Park area (critical locations 20, 22, and 27) that is 113 ft below sea level, mainly due to the shift of pumpage from the Aquia aquifer to the Upper Patapsco aquifer. In the Lower Patapsco aquifer, drawdown for 2002 to 2030 is 220 ft in the Waldorf-La Plata area. The management level is not exceeded in this area, but at Indian Head, it is exceeded by about 50 ft, and the water level is below the top of the Lower Patapsco aquifer. At Bensville, about 86 ft of available drawdown remains in 2030. Results for Scenario 5a fall between results for Scenarios 1 and 5b. About 13 ft of available drawdown remains at Waldorf (critical location 12). Drawdown in the Upper Patapsco aquifer at La Plata only exceeds the management level by about 3 ft. Drawdown at Indian Head exceeds the management level by 43 ft, and is below the top of the Upper Patapsco aquifer.

Scenario 6

Scenario 6 represents the addition of six public-supply wells (or well fields) at new locations, two in each county. The location, pumpage rate, and aquifer for each well were determined in conjunction with county planning officials. The new wells were located within one mile of existing public water-distribution areas to avoid construction of new distribution infrastructure. Locations and information for these hypothetical wells are shown in figure 8 and table 7a, as critical locations 8 and 9 in Calvert County, 17 and 18 in Charles County, and 29 and 30 in St. Mary's County. These new pumpage centers represent additional withdrawals over the rates simulated in Scenario 1. The pumping rate at each site was held constant throughout the entire future simulation. Pumpage rates at all other sites were identical to those in Scenario 1.

In Scenario 6, simulated drawdowns for 2002 to 2030 are generally similar to drawdowns in Scenario 1. Drawdowns are greater at the hypothetical new public-supply wells, but do not exceed or even approach management levels. However, the increased pumpage in the Upper Patapsco aquifer in Calvert and St. Mary's Counties, and increased leakage to the Lower Patapsco aquifer in Charles County cause drawdown to slightly exceed the management level for 2030 in the Upper Patapsco aquifer at La Plata (10 ft of available drawdown remained in Scenario 1). Management levels are also exceeded by 40 ft at Waldorf in the Upper Patapsco aquifer, and by 43 ft at Indian Head in the Lower Patapsco aquifer.

Scenario 7

Scenario 7 simulates increases in pumpage at the PNATS (Patuxent Naval Air Test Station). Because of uncertainties in growth at military facilities, pumpage was increased by 10 percent (Scenario 7a), and 20 percent (Scenario 7b) over 2002 rates. Locations of pumping centers within the facility, and aquifers pumped, were kept the same as in Scenario 1, which simulated 2002 conditions through 2030.

In Scenario 7, heads are a few feet deeper in the Aquia aquifer at Lexington Park than in Scenario 1. Elsewhere, heads are nearly identical to heads in Scenario 1.

Scenario 8

Scenario 8 represents the addition of three major users, one in each county, at new, hypothetical locations. The location, pumping rate, and aquifer for each site were determined in conjunction with county planning officials. Locations and information for these hypothetical wells are shown in figure 8 and table 7a, as critical location 9 in Calvert County, 18 in Charles County, and 28 in St. Mary's County. The pumping rate at each site was held constant throughout the entire future simulation. Pumpage rates at all other sites were identical to those in Scenario 1.

In Scenario 8, additional drawdowns were 49 ft and 66 ft at Huntingtown (Calvert County) and Elms Property (St. Mary's County) respectively, but there were no significant effects elsewhere in those counties. In Charles County, however, the hypothetical major user was located at Billingsley Road near other critical locations in the Waldorf-La Plata area, and caused additional drawdowns at some of those locations. Additional drawdown over Scenario 1 at the hypothetical major user at Billingsley Road was about 77 ft in the Lower Patapsco aquifer, and remaining available drawdown is 383 ft. Additional drawdown at the other critical locations in Charles County ranged up to 30 ft at Barrington Drive and at Waldorf, both in the Lower Patapsco aquifer. Addition of the hypothetical users caused drawdown to exceed the management level slightly (0.2 ft) in the Upper Patapsco aquifer at La Plata.

Discussion of Results

Results of the future pumpage simulations indicate that drawdowns in Calvert and St. Mary’s Counties will not exceed the 80-percent management level under any of the scenarios considered in this study. Charles County, however, cannot supply the required water in 2030, given the simulated scenarios, without drawdowns exceeding 80-percent management levels at some locations. Future pumpage may also cause significant drawdown near the outcrop/recharge areas of the Upper Patapsco and Lower Patapsco aquifers in northwestern Charles County. Although the flow model used in this study cannot accurately simulate hydrogeologic conditions in the shallow subsurface of the outcrop areas, it does indicate that the large simulated increases in pumpage rates in well fields fairly close to the outcrop areas may cause detrimental effects.

In Calvert County, projected ground-water demand could be met without shifting withdrawals to deeper aquifers (Scenario 1). In this scenario, the deepest simulated head for 2030 is about 200 ft below sea level near Solomons, and the lowest remaining available drawdown is 141 ft at Prince Frederick. Even a 20-percent increase above the likely increase in ground-water withdrawals does not cause drawdowns to exceed management levels. Shifting 25 percent of public-supply withdrawals from the Aquia aquifer to the Upper Patapsco aquifer (Scenario 5a) increases remaining available drawdown at Prince Frederick to 157 ft, and shifting 50 percent (Scenario 5b) increases remaining available drawdown at Prince Frederick to 173 ft (about 31 ft more available drawdown than in Scenario 1). Increased withdrawals in the Upper Patapsco and Lower Patapsco aquifers in Calvert County in Scenarios 5a and 5b contribute minimally to drawdowns near the outcrop area in Charles County.

In St. Mary’s County, projected ground-water demand could also be met without shifting withdrawals to deeper aquifers (Scenario 1). In this scenario, the deepest simulated head for 2030 is about 248 ft below sea level in the Aquia aquifer at Lexington Park, and the lowest remaining available drawdown is 71 ft at Charlotte Hall. A 20-percent increase in ground-water withdrawals (Scenario 2b) does not cause drawdowns to exceed management levels. Shifting 25 percent of public-supply withdrawals from the Aquia aquifer to the Upper Patapsco aquifer (Scenario 5a) increases remaining available drawdown at Charlotte Hall to 83 ft, and shifting 50 percent (Scenario 5b) increases remaining available drawdown at Charlotte Hall to 96 ft. Increased withdrawals in the Upper Patapsco aquifer in St. Mary’s County in Scenarios 5a and 5b contribute minimally to drawdowns near the outcrop area in Charles County.

In Charles County, the proximity of the major pumping centers to the outcrop/recharge areas of the Patapsco aquifers, and the relatively shallow depth of the aquifers limit their productive capabilities. Withdrawals from the Magothy aquifer in the Waldorf area cannot be increased significantly above 2002 amounts without lowering heads below management levels. Withdrawals from the Upper Patapsco aquifer in this area can be increased above 2002 amounts (Scenario 1) but probably not enough to accommodate a shift of pumpage from the Magothy aquifer. Shifting pumpage from the Magothy aquifer to the Lower Patapsco aquifer (Scenario 5a and 5b) may cause declines in the water table in the outcrop of the Lower Patapsco and river-water intrusion from the Potomac River. The Potomac River is tidally-influenced fresh water in the area of the cones-of-depression in northwestern Charles County. Potomac River water has average salinity values of 0.09 and 0.23 parts per thousand at two sites in this area (Maryland

Department of Natural Resources, 2005a, b). River-water intrusion into the aquifers may cause the ground water to be unsuitable for some uses, such as human consumption.

Several ground-water alternatives to the modeled scenarios are available for consideration that would help alleviate excessive drawdowns in central Charles County. Although these were not within the scope of this study, it is prudent to mention them.

1. Some pumpage could be shifted from the Magothy, Upper Patapsco, and Lower Patapsco aquifers to the deeper Patuxent aquifer. This alternative would require more information on the hydraulic characteristics and water quality in the Patuxent aquifer.
2. Using optimization techniques, it may be possible to minimize drawdowns in the aquifers in central Charles County and avoid exceedence of the 80-percent management level. However, this would probably not lessen the effects of excessive drawdown in the outcrop areas.
3. Well fields in central and northwestern Charles County could be replaced with well fields farther southeast where aquifer tops (and management levels) are deeper and available drawdown is greater. This would effectively move the cones-of-depression to the southeast, farther from the outcrop areas of the Upper Patapsco and Lower Patapsco aquifers.

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APPENDIX – FLOW-MODEL DESCRIPTION

Model Area, Grid, and Boundaries

The flow model covers an area of 6,642 square miles, between latitudes 37° 50′ and 39° 00′, and longitudes 76° 00′ and 77° 30′ (fig. 1). The model area includes Calvert, Charles, and St. Mary's Counties, but extends north to Washington D.C., east to the Cambridge area, and south and west to include parts of Virginia. The model area was extended beyond the limits of the study area so that the model boundaries would have minimal effect on model results in the area of main interest.

The model area was divided into a finite-difference grid with square, regularly-spaced grid cells one-half mile on each side. The grid was placed in a north/south, east/west orientation, with the horizontal direction (164 columns) slightly larger than the vertical direction (162 rows).

Boundary conditions were entered at the top, bottom and lateral edges of the model domain (fig. 7). The top of the model was entered as a specified-head boundary (model layer 1). The estuaries (Chesapeake Bay, the Potomac River and other tidal rivers) were entered as a constant head at sea level. The Surficial aquifer (the land portions of the model area) was entered as constant heads of the water-table altitude. The water-table altitude was estimated using a geographic information system (GIS) process that incorporated land-surface elevation and perennial stream altitudes. The bottom of the model, which is the Arundel Clay, was represented as a no-flow boundary, assuming that the thick, low-permeability clay and silt of this unit would not allow significant leakage between the Lower Patapsco aquifer and the underlying Patuxent aquifer.

The Fall Line was simulated as a no-flow boundary because the Coastal Plain aquifers do not extend northwest of this line. In areas where an aquifer extends beyond the model edges, the boundary was simulated with a head-dependant flux boundary (referred to as a General Head Boundary, or GHB). The flux (or ground-water flow) into or out of the model at this boundary was calculated by the model using a conductance value, a head value entered at the GHB boundary, and the head calculated within the model domain. Conductance values were generally entered as 500 feet squared per day (ft^2/d), which allows the model heads to differ slightly from the heads entered at the boundary. Heads entered at the GHB boundaries were estimated from potentiometric maps where available, and from previous modeling studies (Fleck and Vroblesky, 1996) where potentiometric maps are not available. No-flow boundary conditions were entered where model edges truncate confining units, because flow is predominantly vertical in the confining units.

Layering Scheme

The vertical section was divided into 11 model layers, in which each major aquifer is represented by a model layer, alternating with model layers representing confining units (fig. 7). From top to bottom, the layering scheme comprises the Surficial, Piney Point/Nanjemoy, Aquia, Magothy, Upper Patapsco, and Lower Patapsco aquifers. The intervening confining units are the Chesapeake, Nanjemoy, Brightseat, Upper Patapsco, and Middle Patapsco confining units. The Patuxent aquifer was not simulated in this model.

Some aquifers and confining units do not extend throughout the entire model area. In areas where a unit thins laterally to zero thickness (and in reality is not present), a minimum thickness of one foot was maintained, the horizontal hydraulic conductivity was assigned a very low value to prevent horizontal water flow, and the vertical hydraulic conductivity was assigned a very high value to allow vertical water flow (leakage). This is necessary to allow vertical flow through the model layer, even where the hydrogeologic unit is absent. In areas where an aquifer undergoes a facies change (the unit is present but not as an aquifer) the layer was assigned horizontal and vertical hydraulic conductivity values appropriate for a confining unit.

Time Discretization

The historical (calibration) model simulation ran from 1900 until 2002. Although no pumping records exist for the period before 1900, the population at that time was only 15 percent of the 2002 population (fig. 6), and this is considered a prepumping condition.
An initial steady-state prepumping stress period was run prior to 1900. The period 1900 to 2002 was divided into four stress periods, ending at 1952, 1982, 1994, and 2002. These periods correspond to previous studies that produced potentiometric maps (Otton, 1955; Chapelle and Drummond, 1983; Achmad and Hansen, 1997) for the region. Potentiometric maps for each aquifer were calculated by the flow model and compared to measured heads for the appropriate time during model calibration.

For future scenarios, three stress periods were simulated, starting in 2003 and ending at 2010, 2020, and 2030, to correspond with population projections. Each stress period was divided into 10 equal time steps, and heads were calculated at the end of each time step. For each aquifer, potentiometric maps were generated, which show heads at the end of each stress period.

Pumpage

Ground-water pumpage was entered in the flow model at discrete points that correspond to well locations. Pumpage was held constant during each stress period described above. Major-user pumpage was entered for the location and aquifer for each Ground-water Appropriation Permit (GAP) in the study area, and for the surrounding counties in Maryland. Many GAPs include multiple production wells, but most of those were simulated as single wells in the model. A few GAPs include multiple wells that are widely dispersed; for these GAPs, pumpage at individual wells was simulated. Total major-user pumpage simulated for 2002 was 3.33 million gallons per day (Mgal/d), 8.96 Mgal/d, and 5.29 Mgal/d for Calvert, Charles, and St. Mary's Counties, respectively (tab. 5).

Domestic pumpage was simulated differently than major-user pumpage. There are too many domestic wells to simulate individually, so "delegate wells" were used to represent pumpage from many individual domestic wells. The number and distribution of delegate wells were based on the estimated pumpage distribution in election districts and aquifers shown in table 4. Each delegate well represents 250 domestic wells pumping 162 gallons per day (gpd) each in 2002. The pumping rate was estimated from a per-capita water-use rate of 60 gpd (Andreasen, 2002) multiplied by an average household size for the region of 2.7. Delegate wells were placed in such a way as to approximate population centers reliant on domestic supply; more delegates were placed in these areas and fewer were placed in less-populated areas and areas reliant on public-water supply.

For historical (1952, 1982, and 1994) and future (2010, 2020, and 2030) stress periods, the same distribution of delegate wells was used as in the 2002 stress period. However, the rate of withdrawal at each well was adjusted to reflect the difference in population from the 2002 population. For historical simulations, the fraction of 2002 population for each county (shown in table 3) was multiplied by the 2002 withdrawal rate for each delegate well to obtain withdrawal rates for 1952, 1982, and 1994. For future simulations, the fractional increase over the 2002 population for each election district in each county (shown in table 4) was multiplied by the 2002 withdrawal rate for each delegate well to obtain withdrawal rates for 2010, 2020, and 2030.

Calibration

The ground-water flow model was calibrated by entering historical pumpage for the period 1900 through 2002, running the model using initial estimates of model inputs, and comparing model-calculated heads with measured heads at the end of each stress period. Based on residuals (the difference between measured and calculated heads), adjustments were made to model inputs, and the process was repeated until a good match was obtained between measured and calculated heads. Statistical parameters (primarily the mean error and the root-mean-square) were calculated for each aquifer and each stress period to provide a quantitative assessment of model calibration (tab. 8).

Estimates of inputs for initial model runs were obtained from previous studies, file sources, and from the six test wells drilled into the Upper Patapsco and Lower Patapsco aquifers. Inputs that were adjusted during model calibration were primarily horizontal hydraulic conductivity for the aquifers, vertical hydraulic conductivity for the confining units, and to a lesser extent, lateral flow boundaries. Inputs that were not adjusted during calibration include storativity, altitude of aquifer tops and bottoms, and altitude of the water table (constant-head boundary in layer 1).

Although model results were evaluated at the end of each stress period (1900, 1952, 1982, 1994, and 2002), greater weight was given to the last stress period. More head measurements were available for this period, and the pumpage data were considered more reliable than for previous periods. Figures 4a through 4e show simulated heads as potentiometric contour lines and measured water levels at observation wells for 2002.

Calibration is considered good for the Piney Point, Aquia, and Magothy aquifers. These aquifers are fairly homogeneous, and can be easily characterized by model layers. Calibration is not considered as good for the Upper Patapsco and Lower Patapsco aquifers. Sparse data are available for these aquifers in many parts of the study area, and existing data indicate that they are extremely variable, with significant vertical and lateral heterogeneities. The variability of these aquifers makes them difficult to characterize as model layers in a study of this scale. Residuals range as high as 24 ft in the Upper Patapsco aquifer, and 39 ft in the Lower Patapsco aquifer. Although the model may not accurately simulate measured heads at some individual wells, it is considered suitable to characterize the regional flow system, and to evaluate the production capabilities of the aquifer system.

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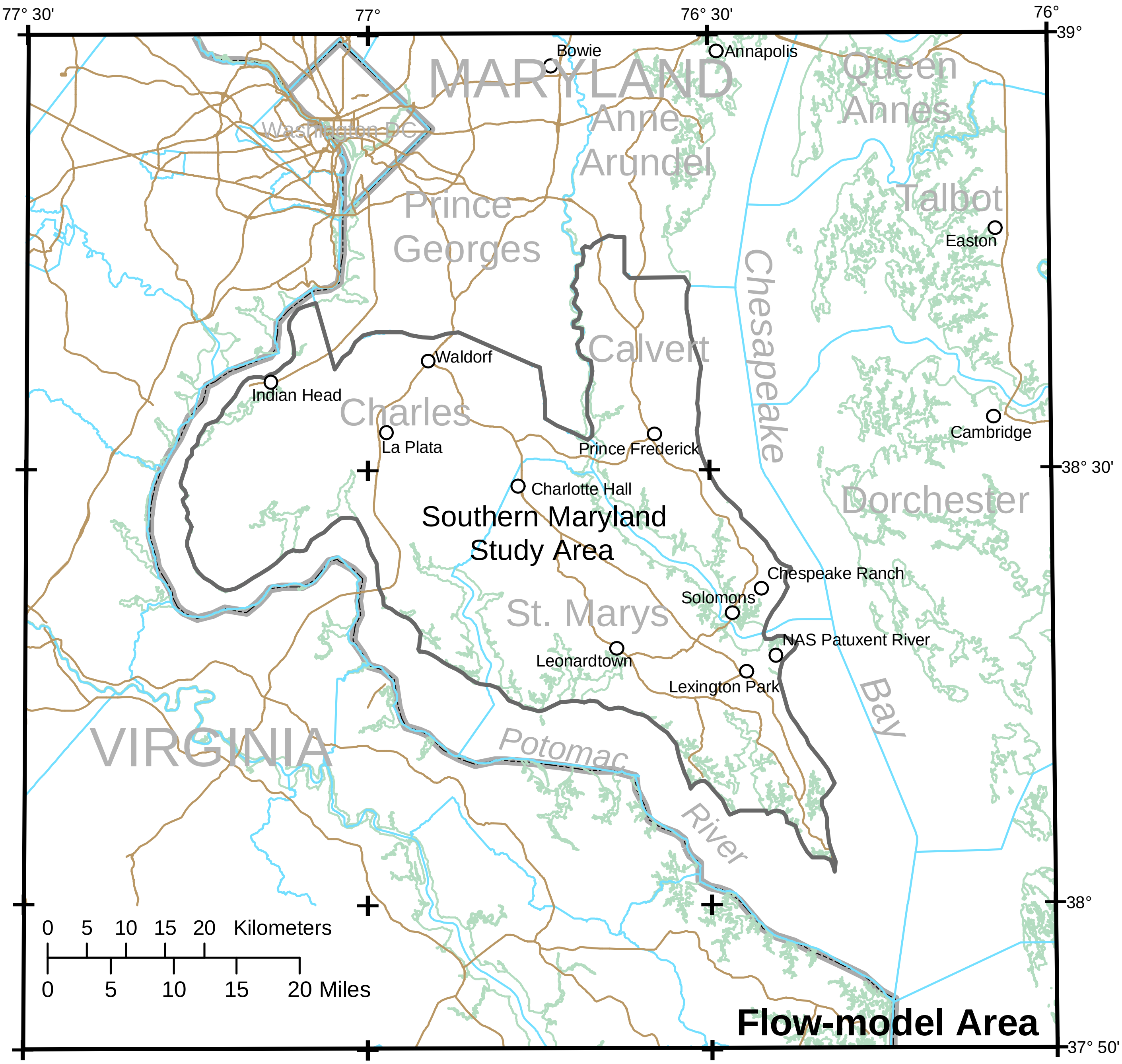
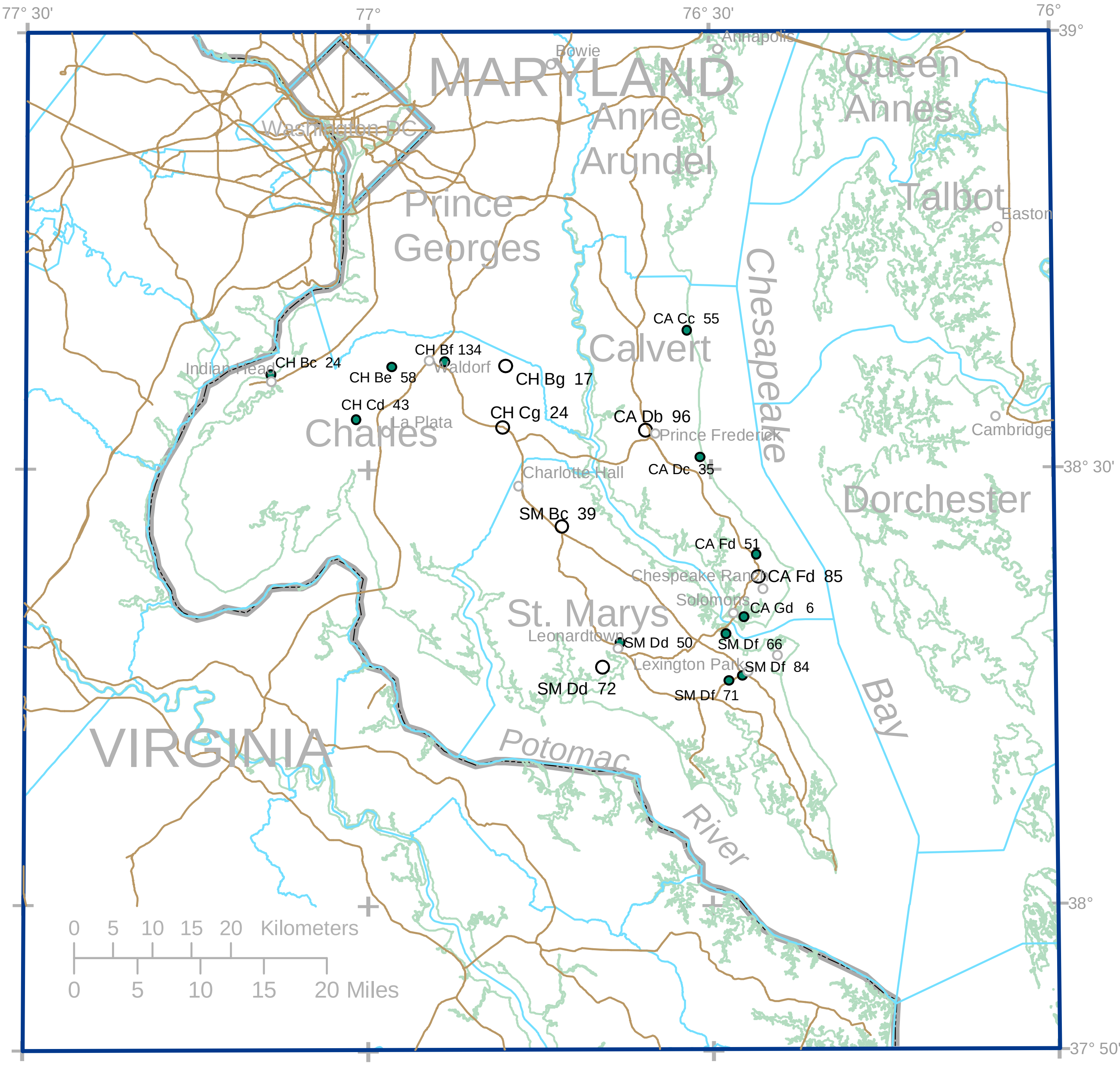


Figure 1. Locations of study area and flow-model area.



Explanation

SM Dd 72	Location of test well and well number
CA Df 66	Location of well with hydrograph and well number

Figure 2. Locations of test wells shown in table 2 and hydrographs shown in figure 5.

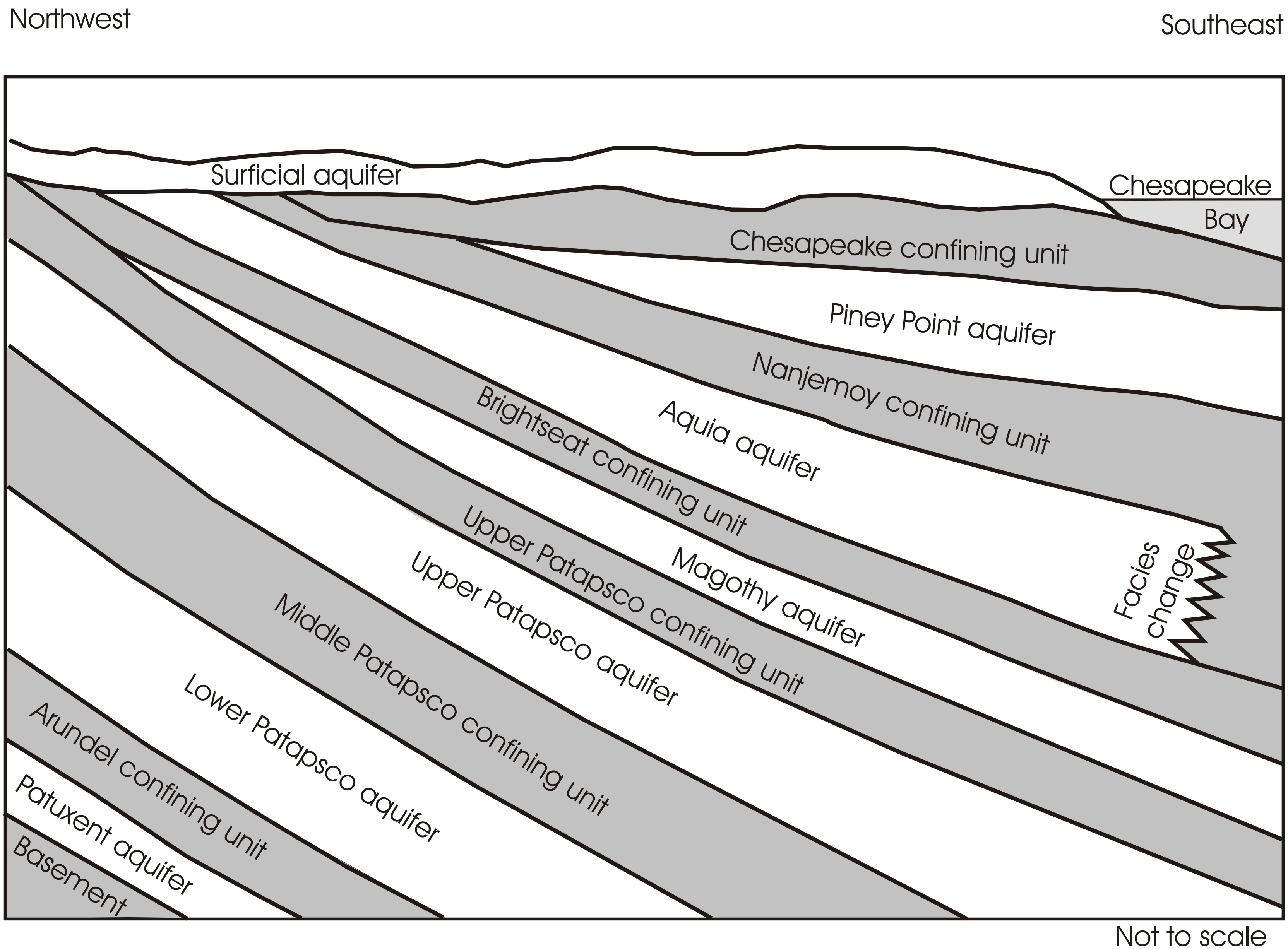


Figure 3. Schematic cross section showing the hydrogeologic units in Southern Maryland.

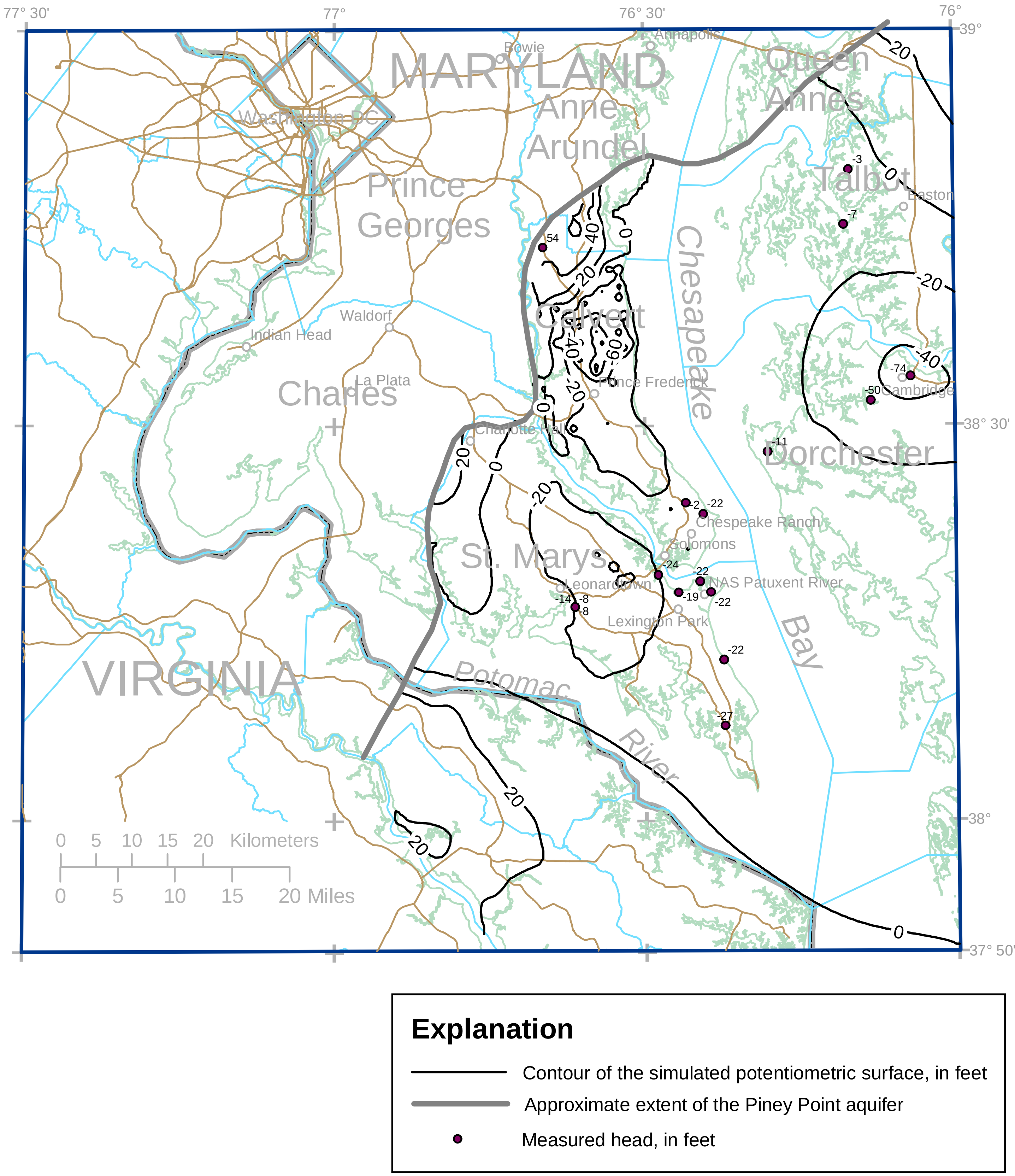


Figure 4a. Simulated potentiometric surface in the Piney Point aquifer, 2002.

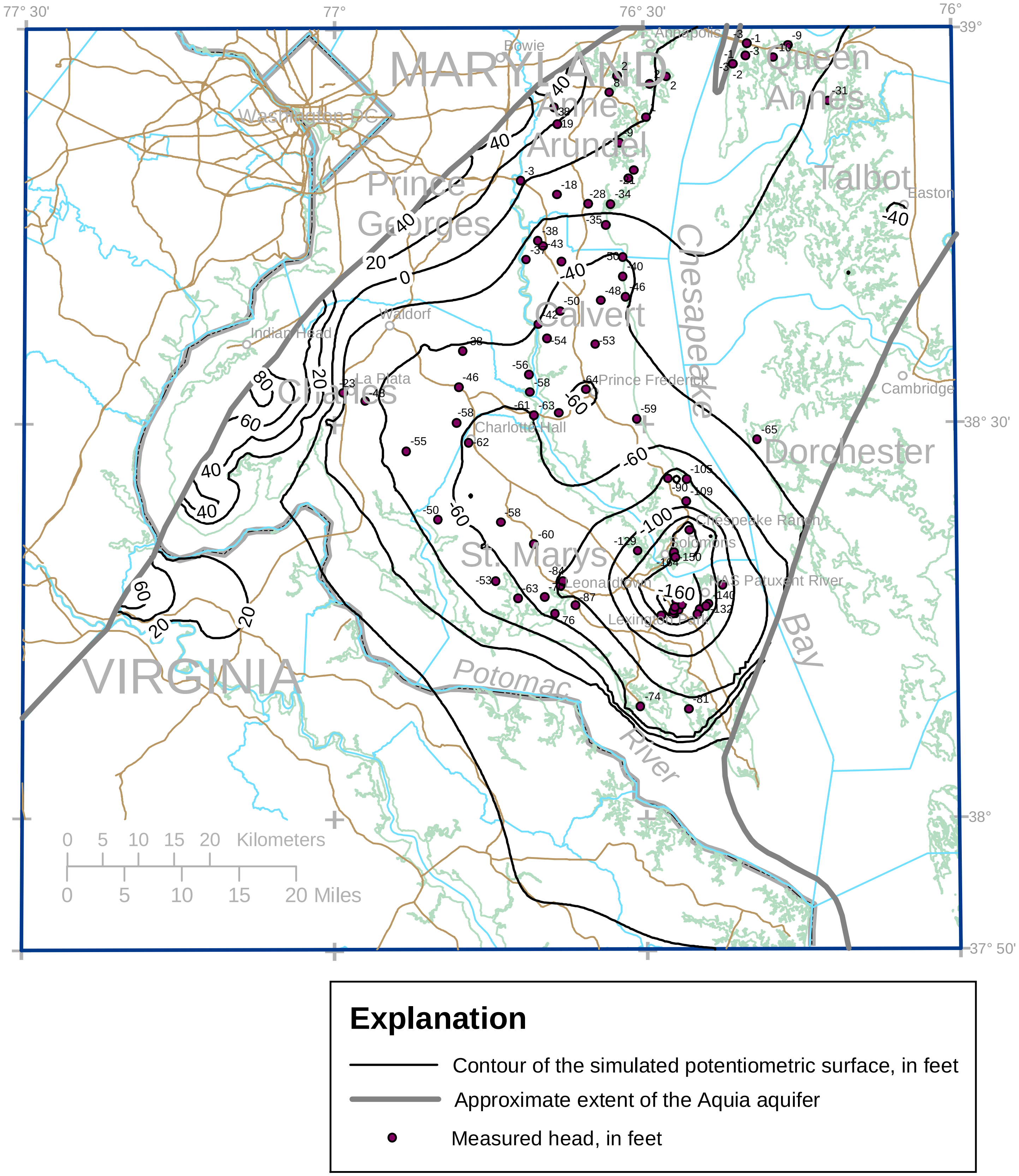


Figure 4b. Simulated potentiometric surface in the Aquia aquifer, 2002.

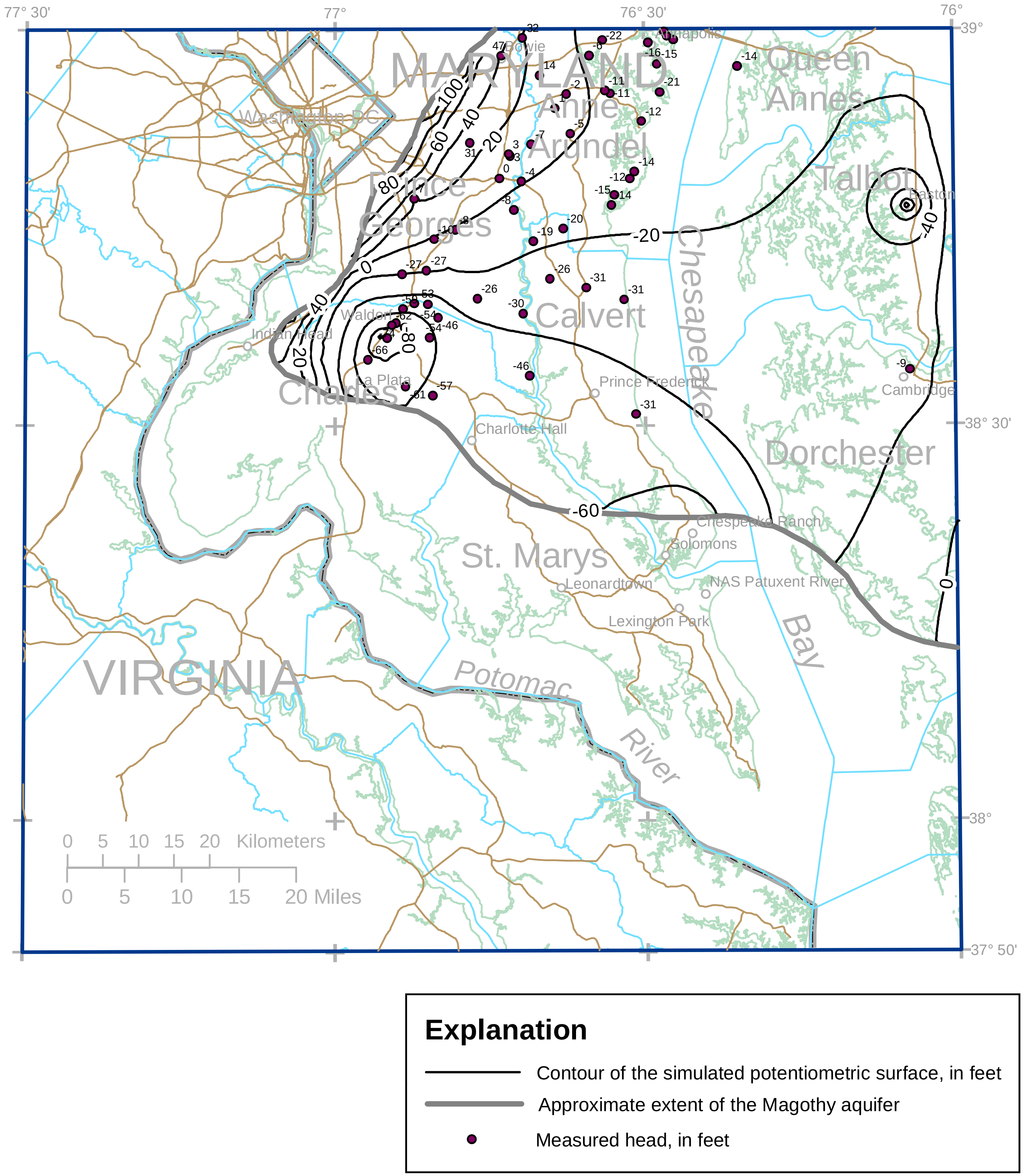


Figure 4c. Simulated potentiometric surface in the Magothy aquifer, 2002.

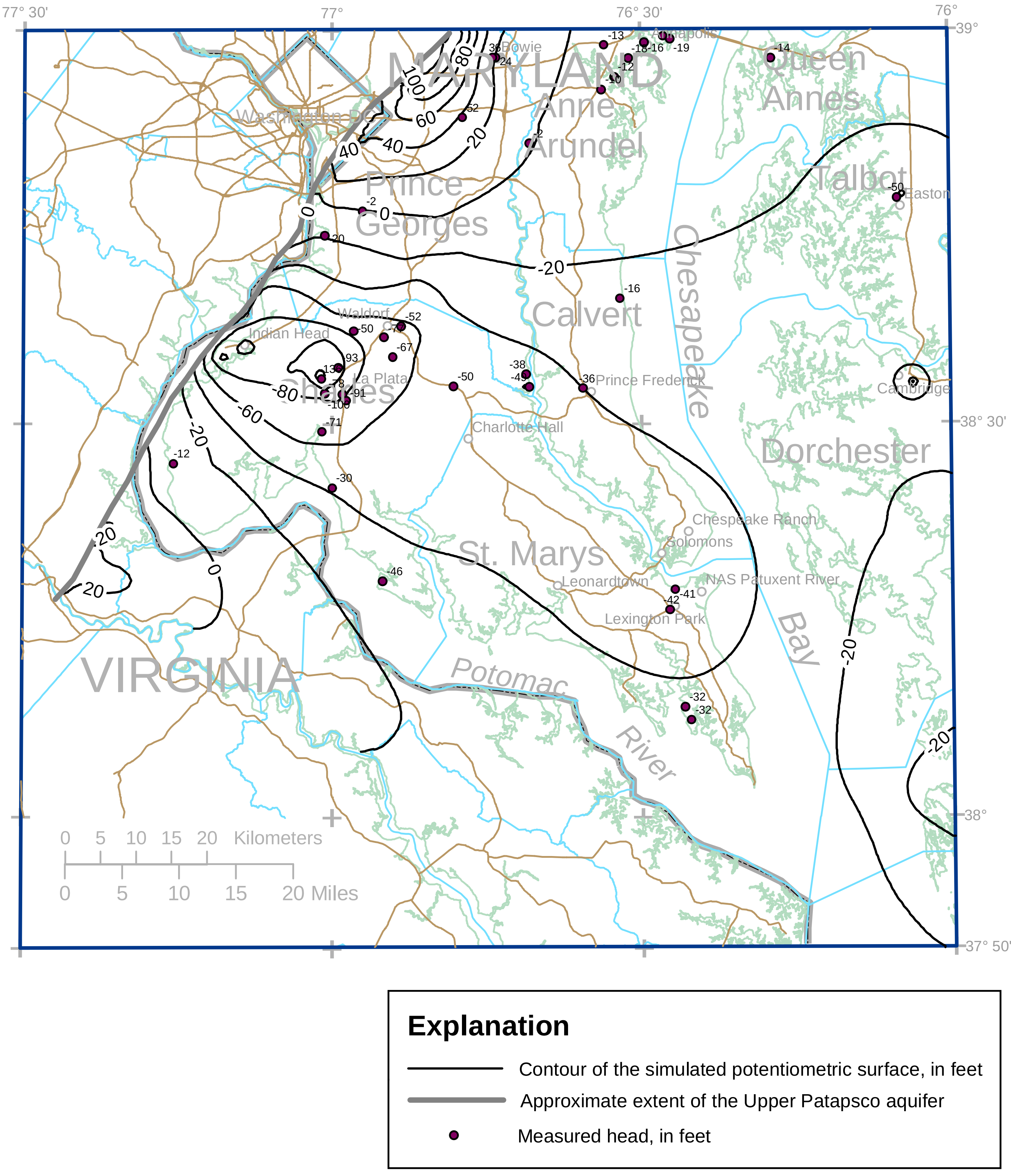
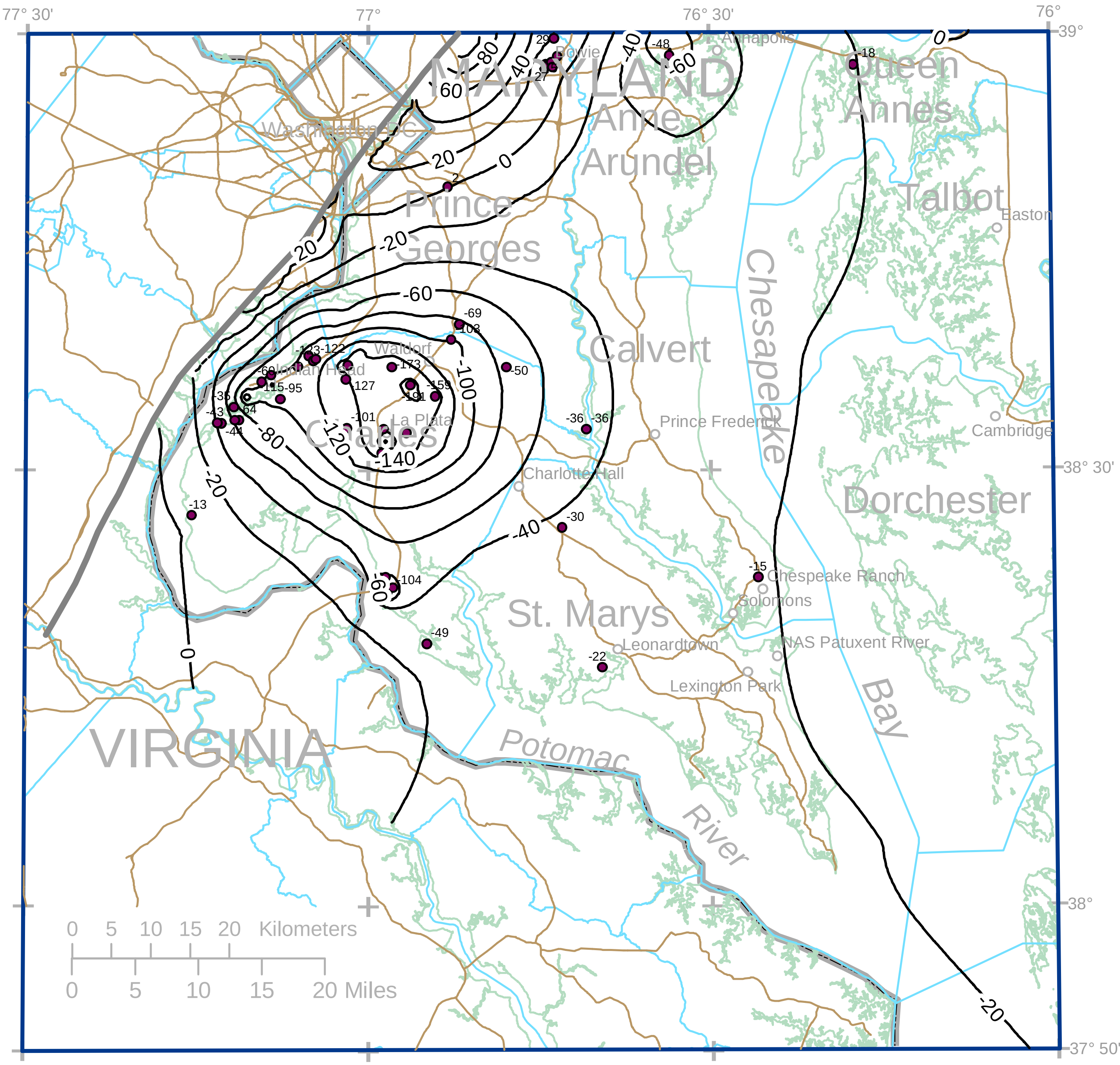


Figure 4d. Simulated potentiometric surface in the Upper Patapsco aquifer, 2002.



Explanation

Contour of the simulated potentiometric surface, in feet

Approximate extent of the Lower Patapsco aquifer

Measured head, in feet

Figure 4e. Simulated potentiometric surface in the Lower Patapsco aquifer, 2002.

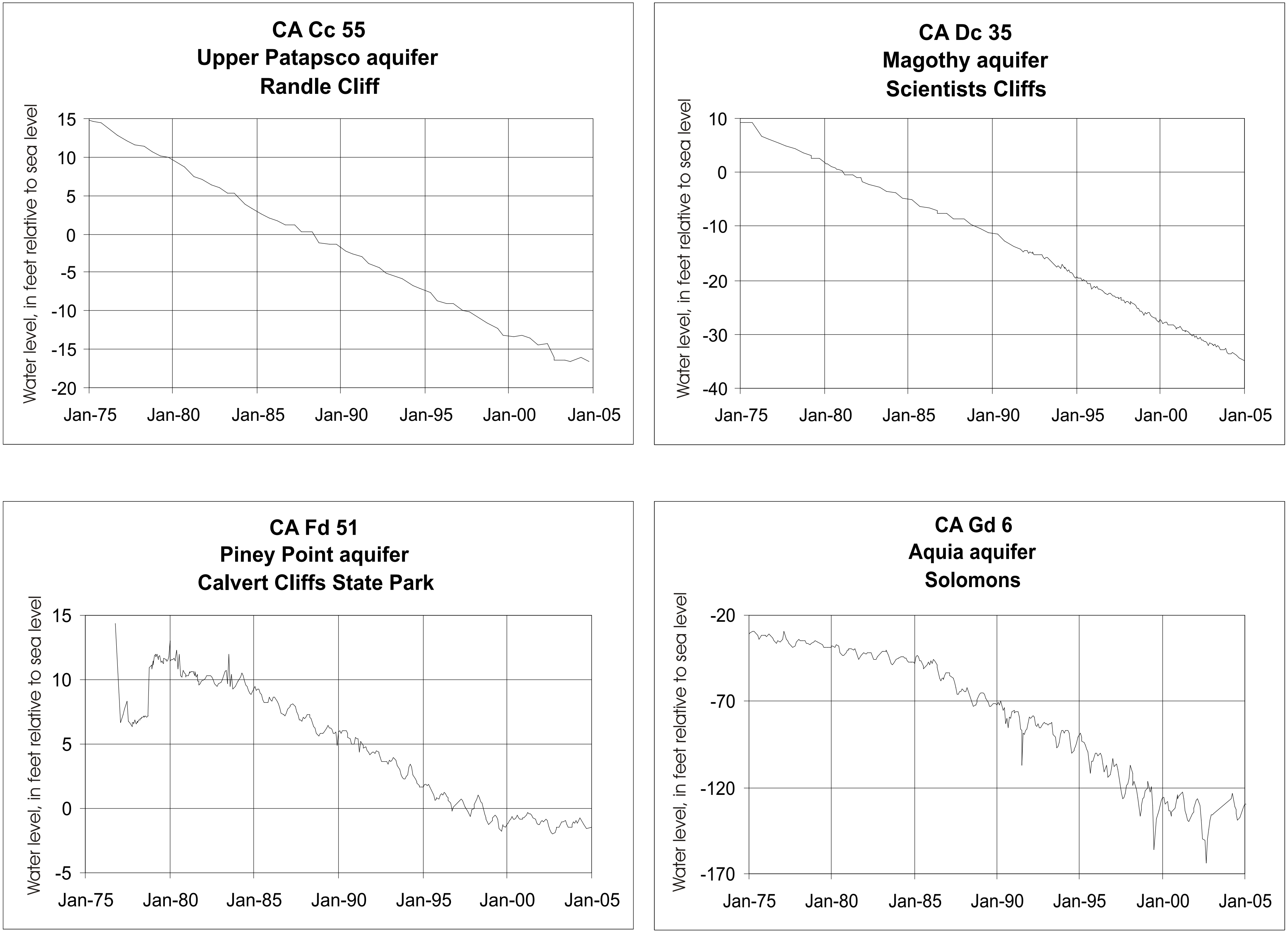


Figure 5a. Hydrographs showing long-term water-level trends in Calvert County.

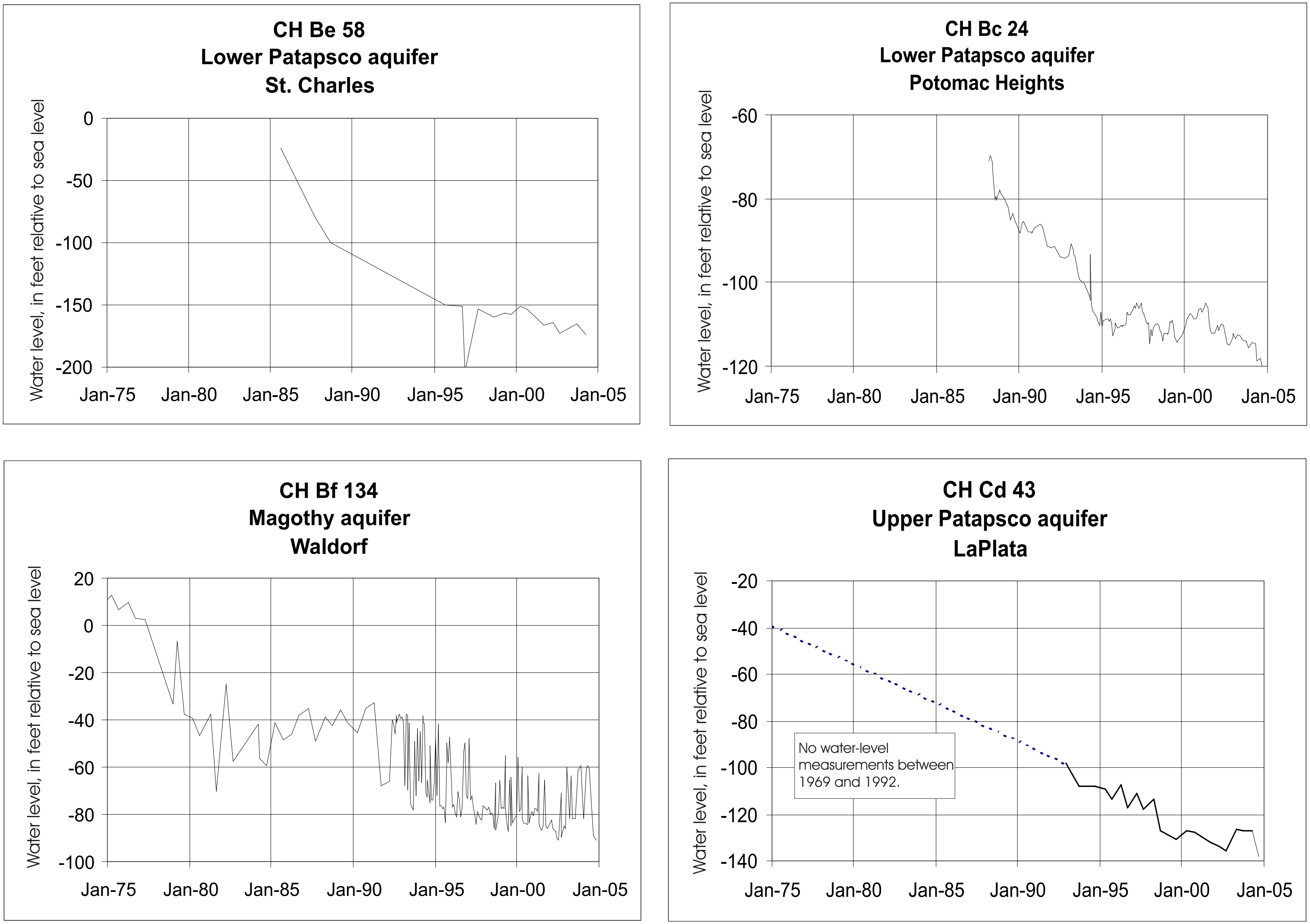


Figure 5b. Hydrographs showing long-term water-level trends in Charles County.

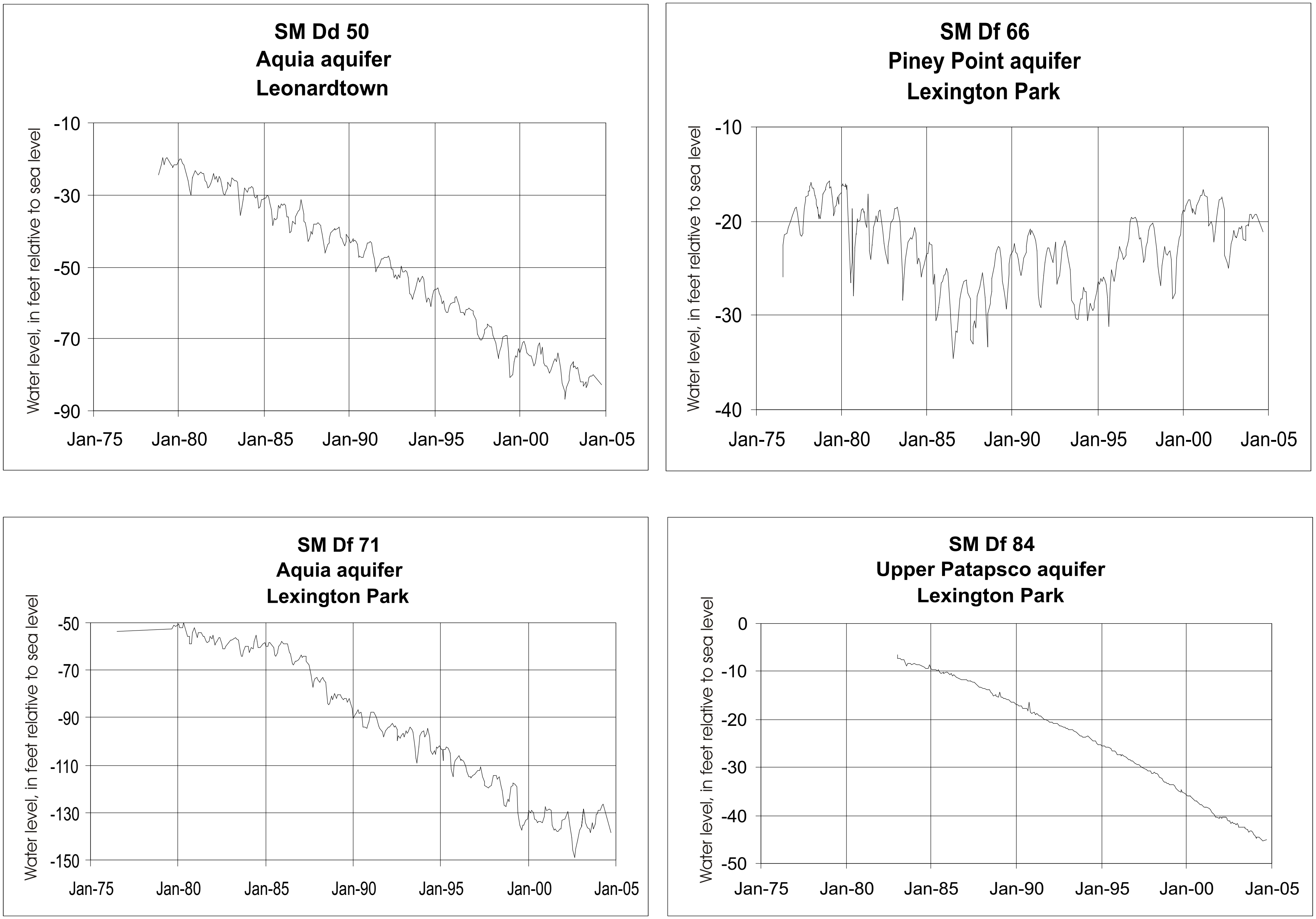
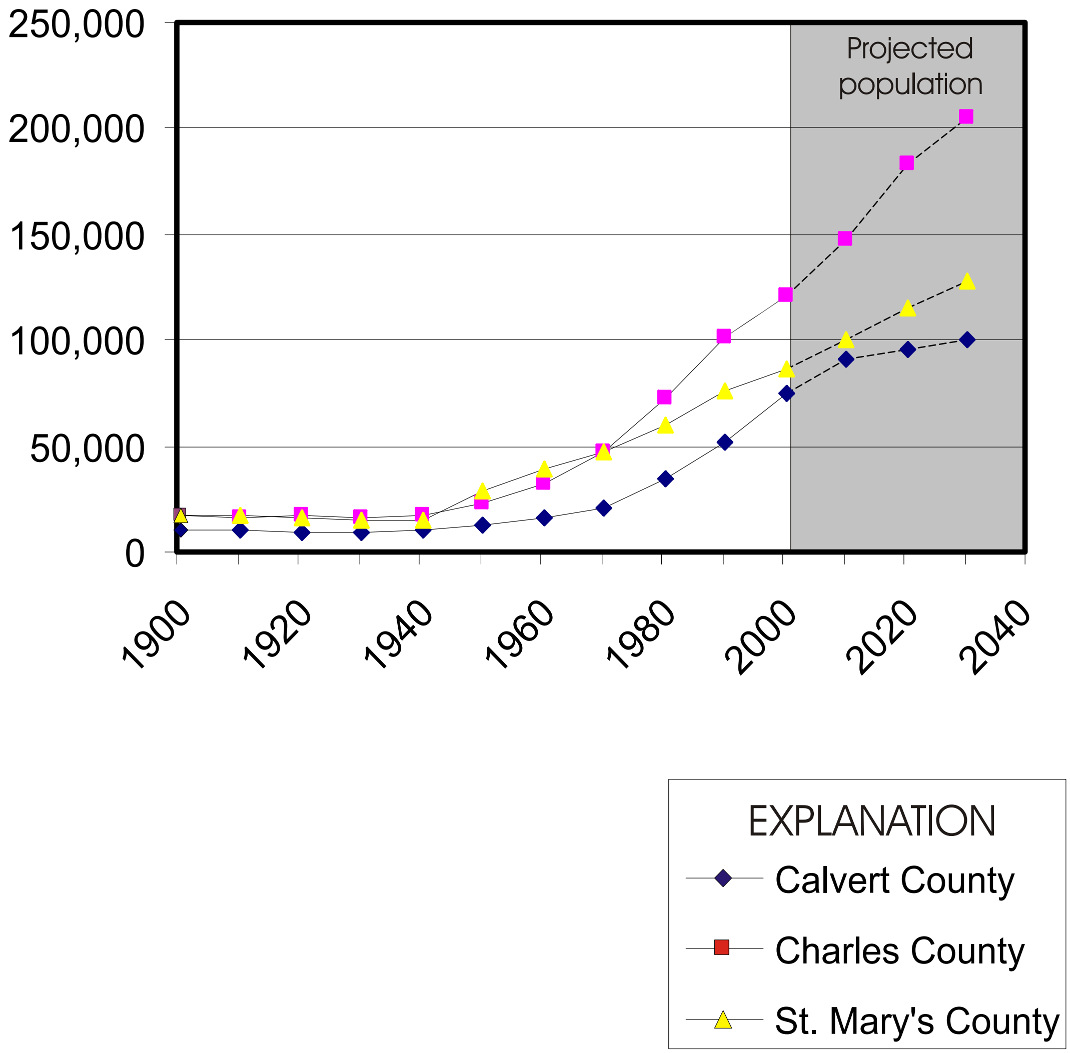


Figure 5c. Hydrographs showing long-term water-level trends in St. Mary's County.



<u>Sources of data:</u>

1900-1990	U.S. Census Bureau, 1995
2000	U.S. Census Bureau, 2003
2010-2030	Calvert County Department of Planning and Zoning
	Charles County Department of Planning and Growth Management
	St. Mary's County Department of Land Use and Growth Management

Figure 6. Historic and projected population in Calvert, Charles, and St. Mary's Counties.

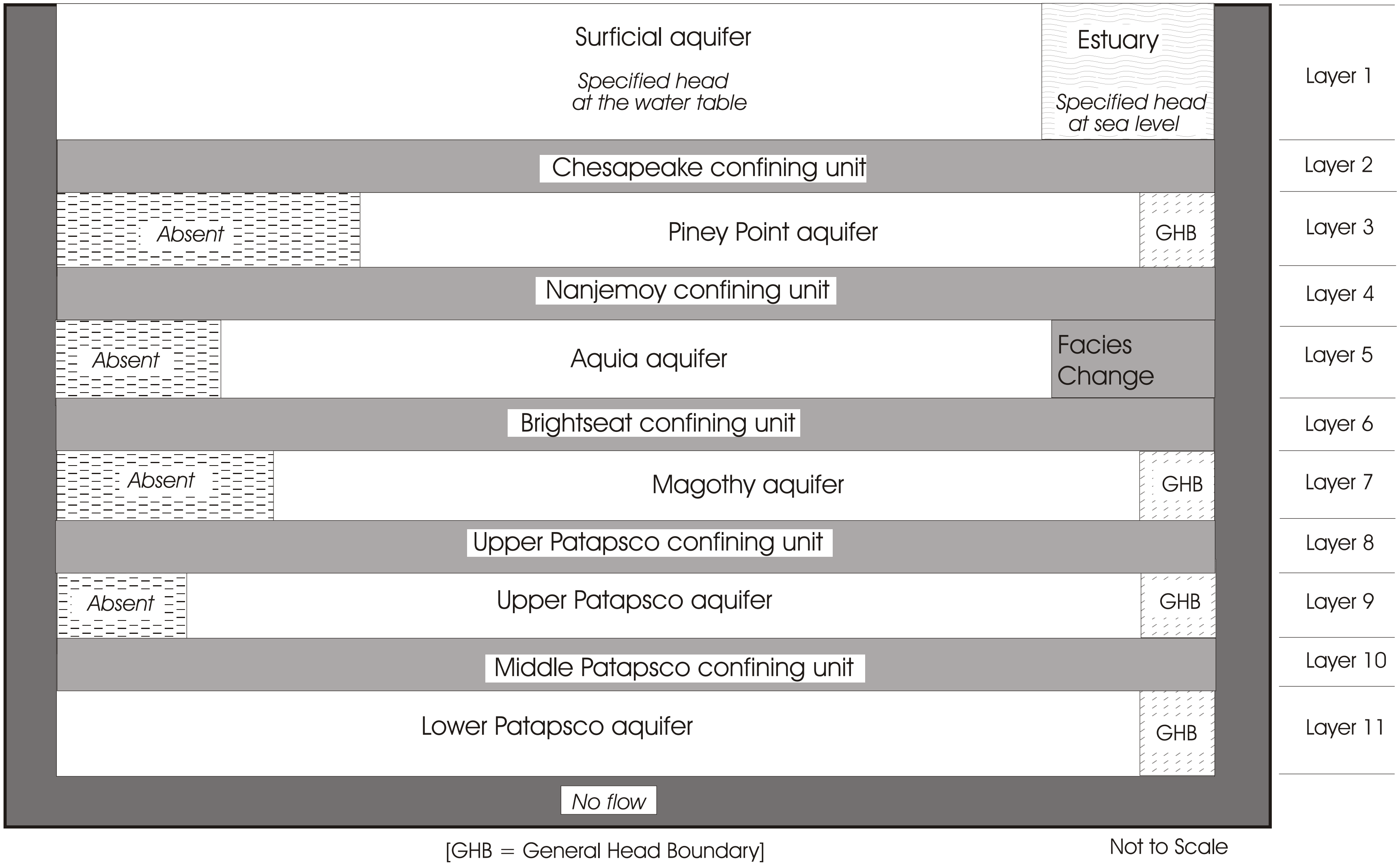
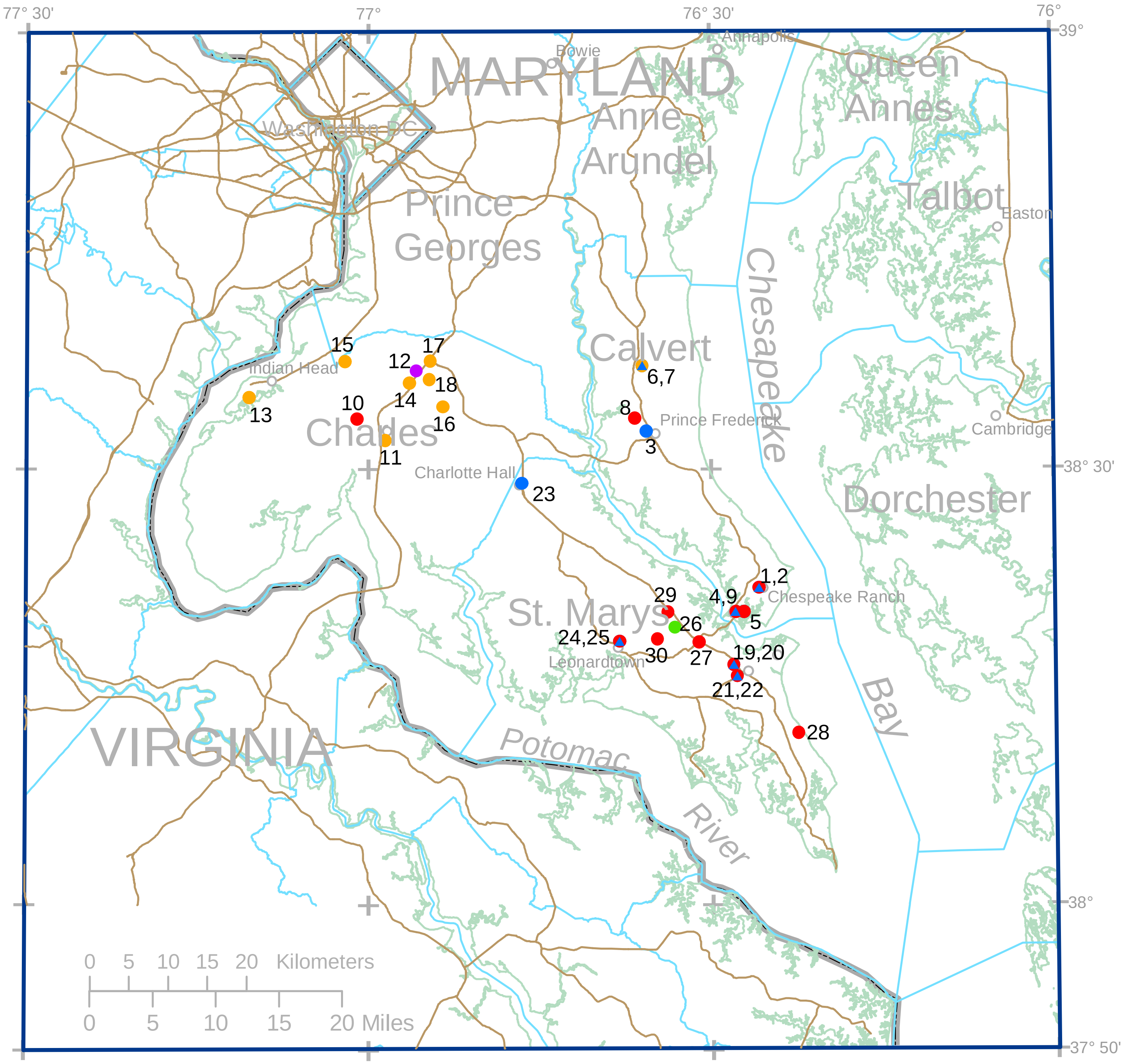


Figure 7. Conceptualization of the ground-water flow model.



Explanation

3 Critical location with model results summarized in table 7
Number refers to Map ID shown in table 7
Aquifer codes shown below

- Piney Point
- Aquia
- Magothy
- Upper Patapsco
- Lower Patapsco
- Two aquifers shown at same location

Figure 8. Critical locations for model results shown in table 7.

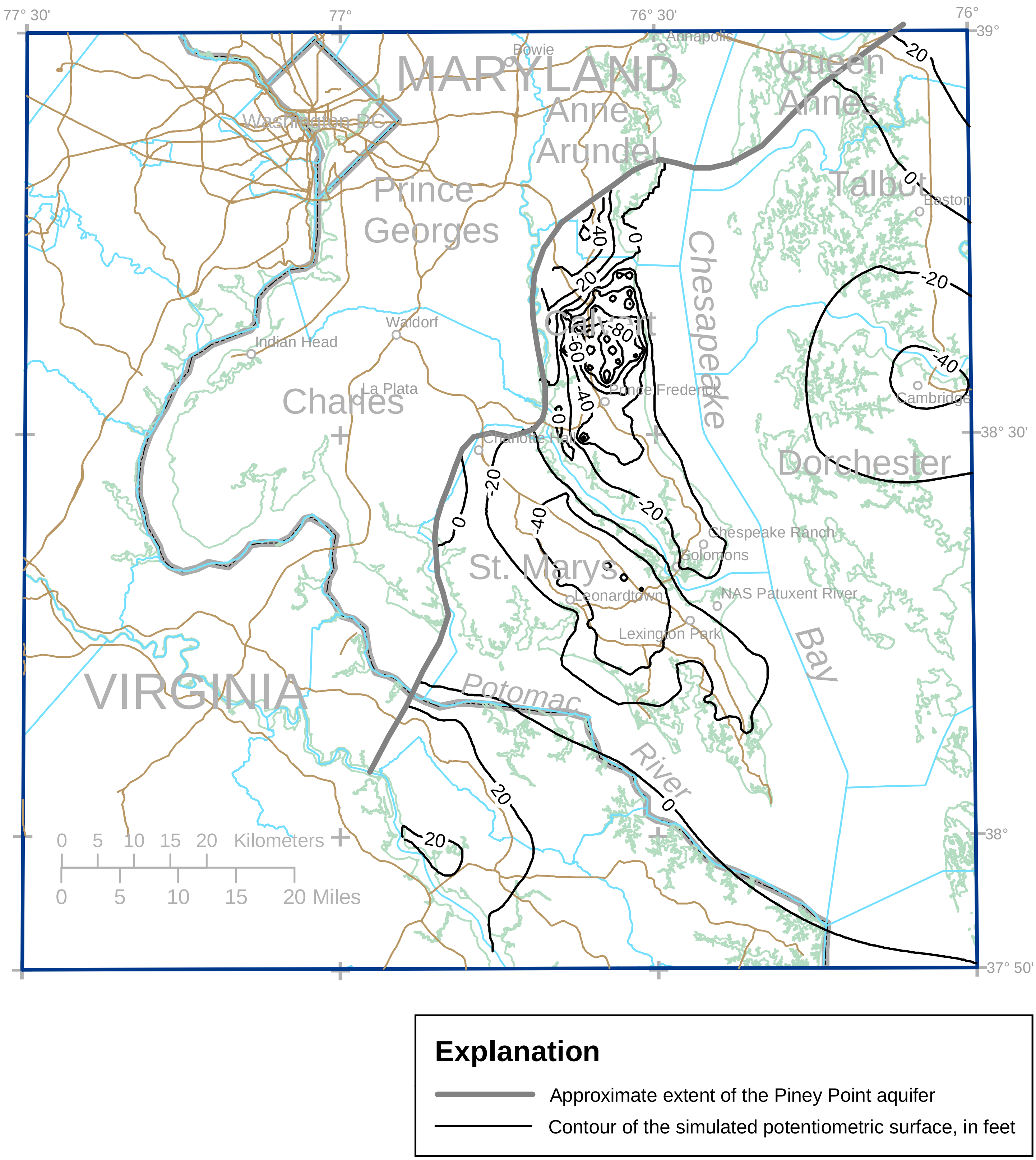
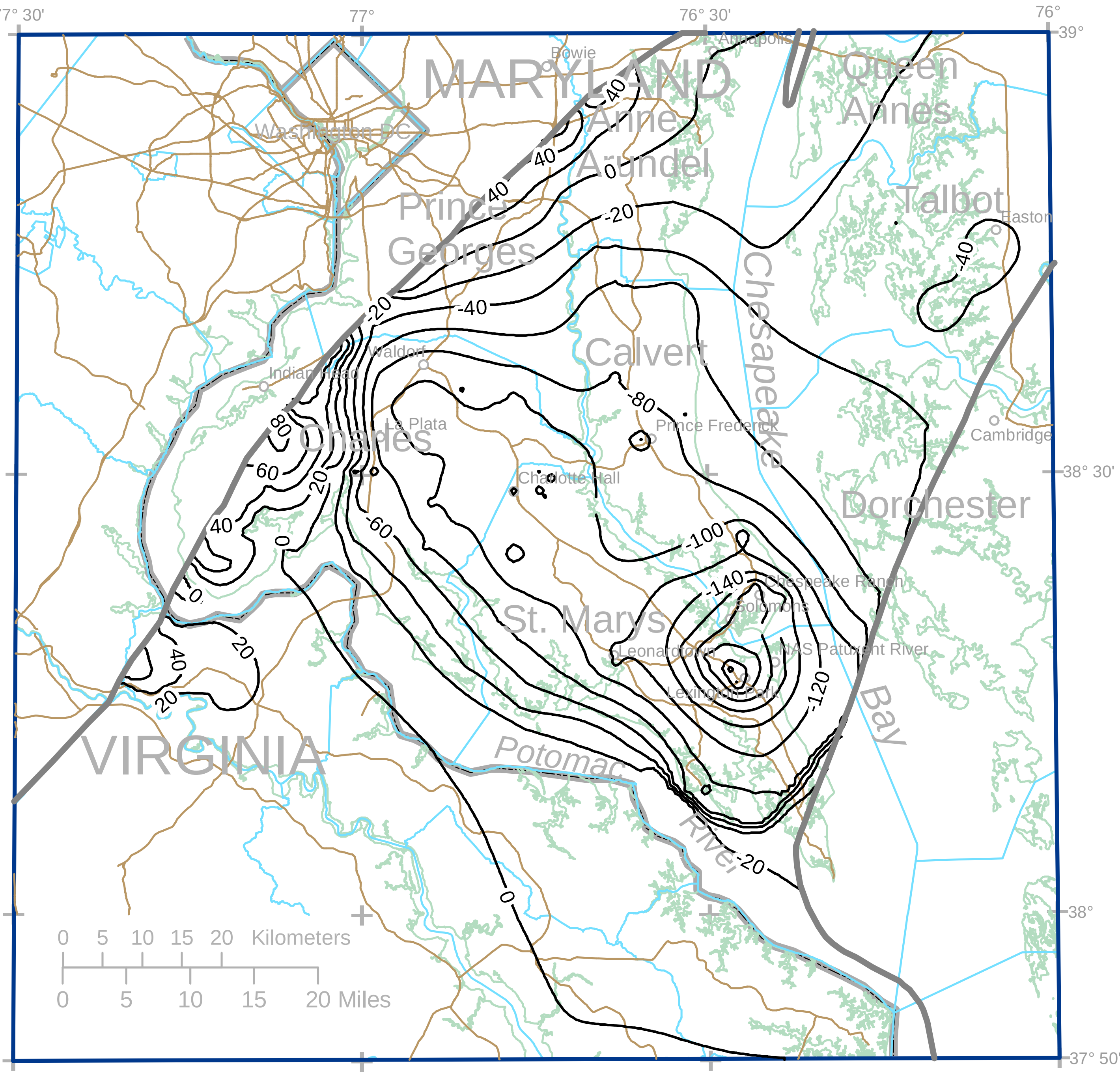


Figure 9a. Simulated potentiometric surface in the Piney Point aquifer, 2030, based on Scenario 1.



Explanation

Contour of the simulated potentiometric surface, in feet

Approximate extent of the Aquia aquifer

Figure 9b. Simulated potentiometric surface in the Aquia aquifer, 2030, based on Scenario 1.

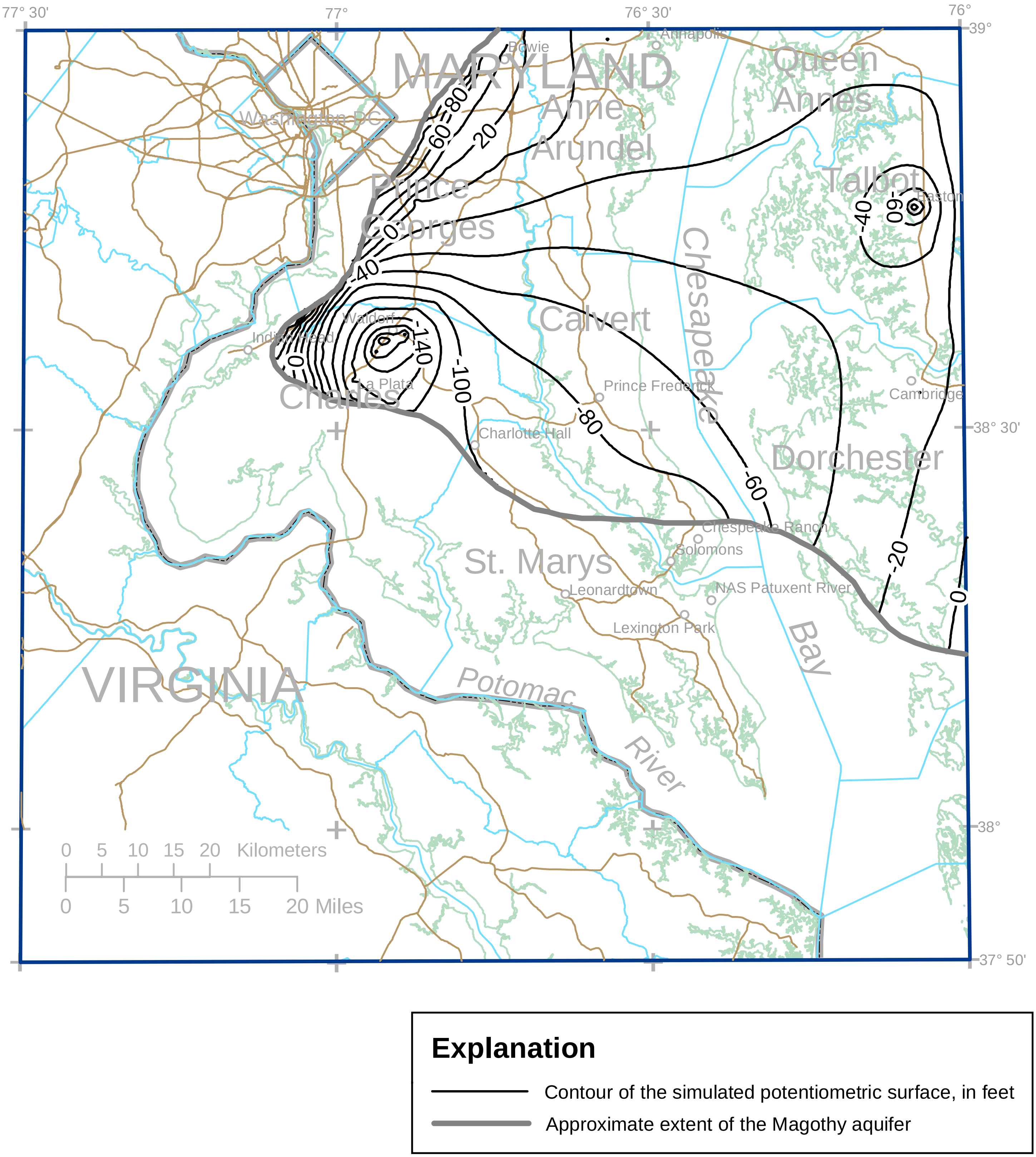
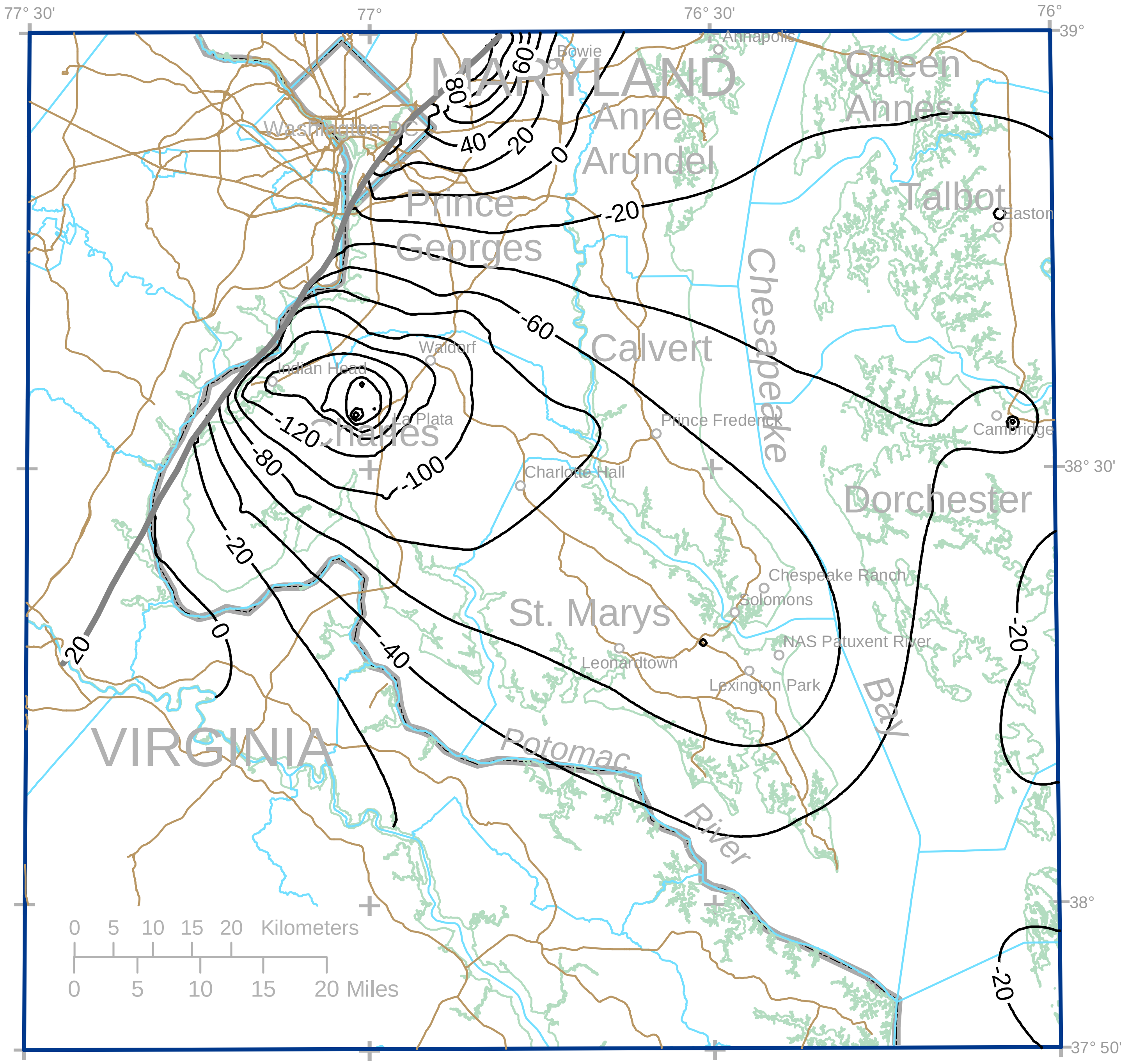


Figure 9c. Simulated potentiometric surface in the Magothy aquifer, 2030, based on Scenario 1.

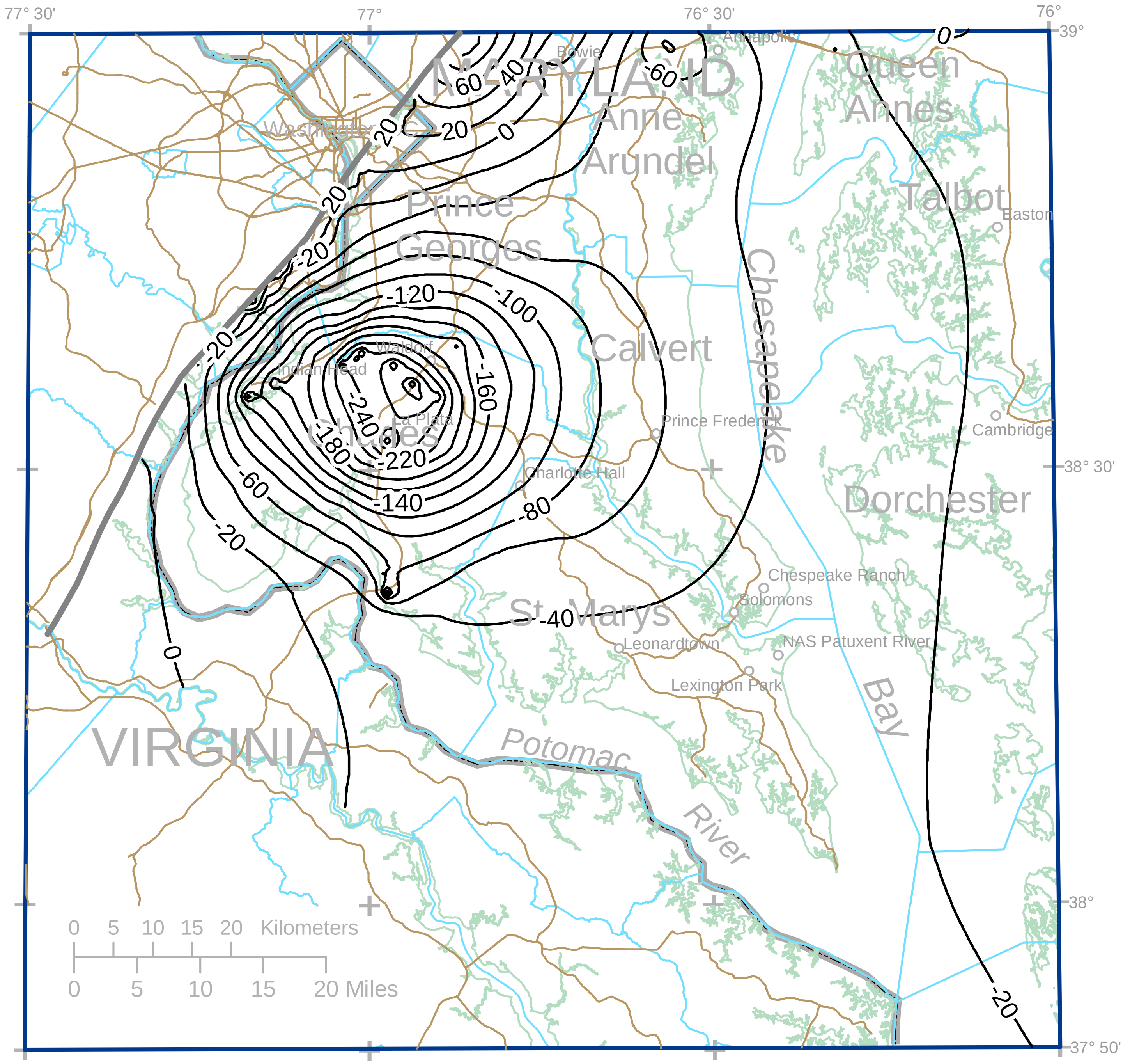


Explanation

Contour of the simulated potentiometric surface, in feet

Approximate extent of the Upper Patapsco aquifer

Figure 9d. Simulated potentiometric surface in the Upper Patapsco aquifer, 2030, based on Scenario 1.



Explanation

(black line)	Contour of the simulated potentiometric surface, in feet
(gray line)	Approximate extent of the Lower Patapsco aquifer

Figure 9e. Simulated potentiometric surface in the Lower Patapsco aquifer, 2030, based on Scenario 1.

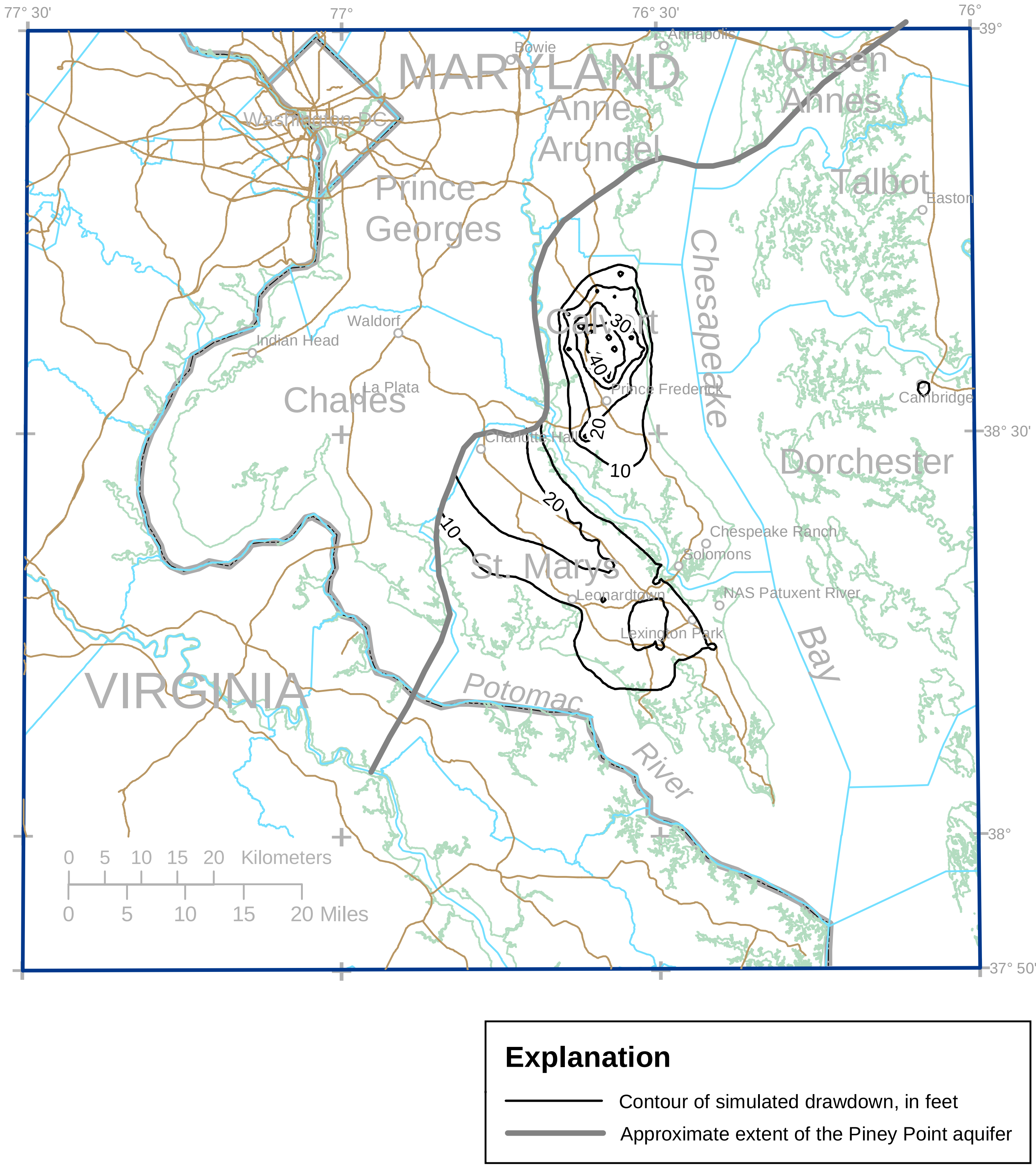
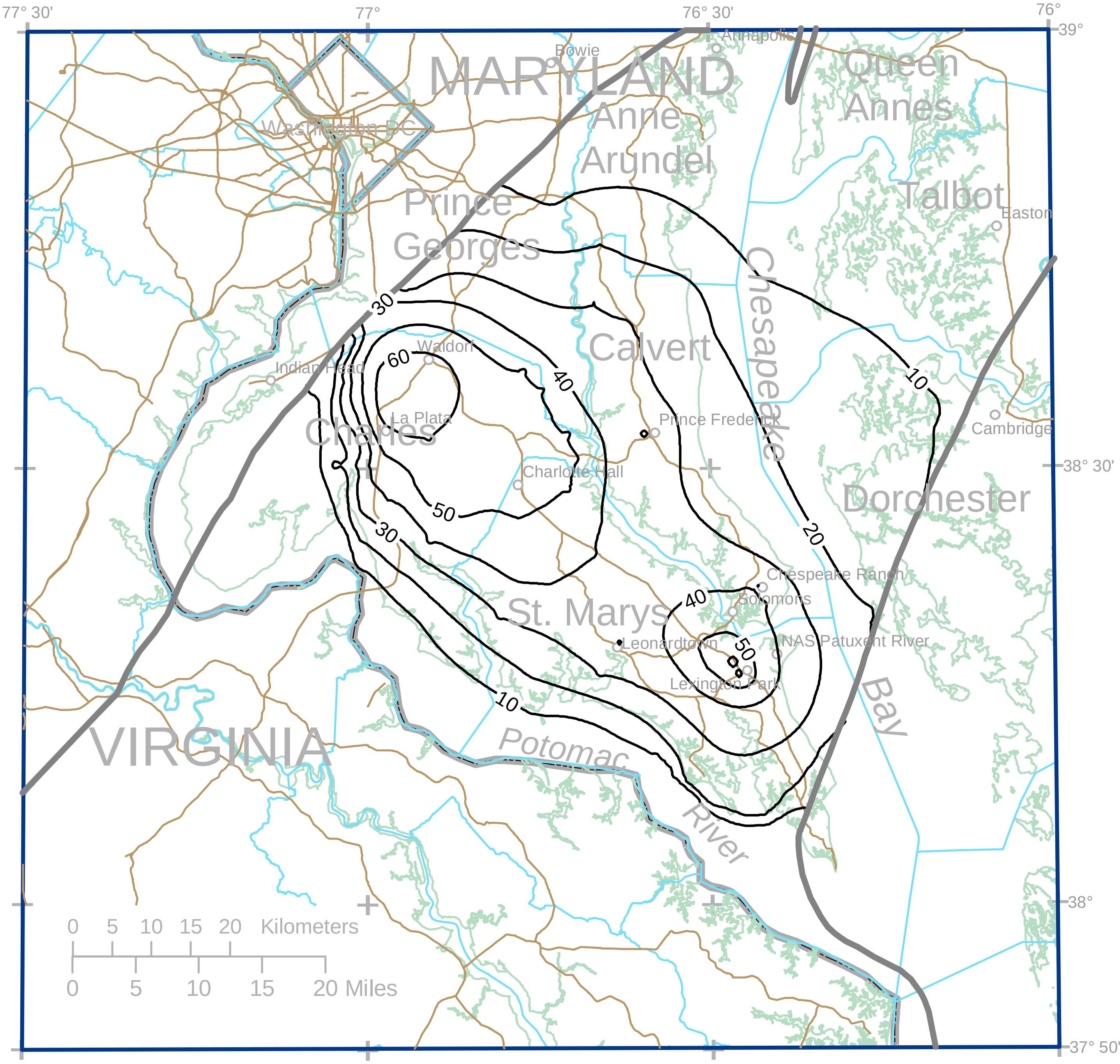


Figure 10a. Simulated drawdown in the Piney Point aquifer, 2002 to 2030, based on Scenario 1.

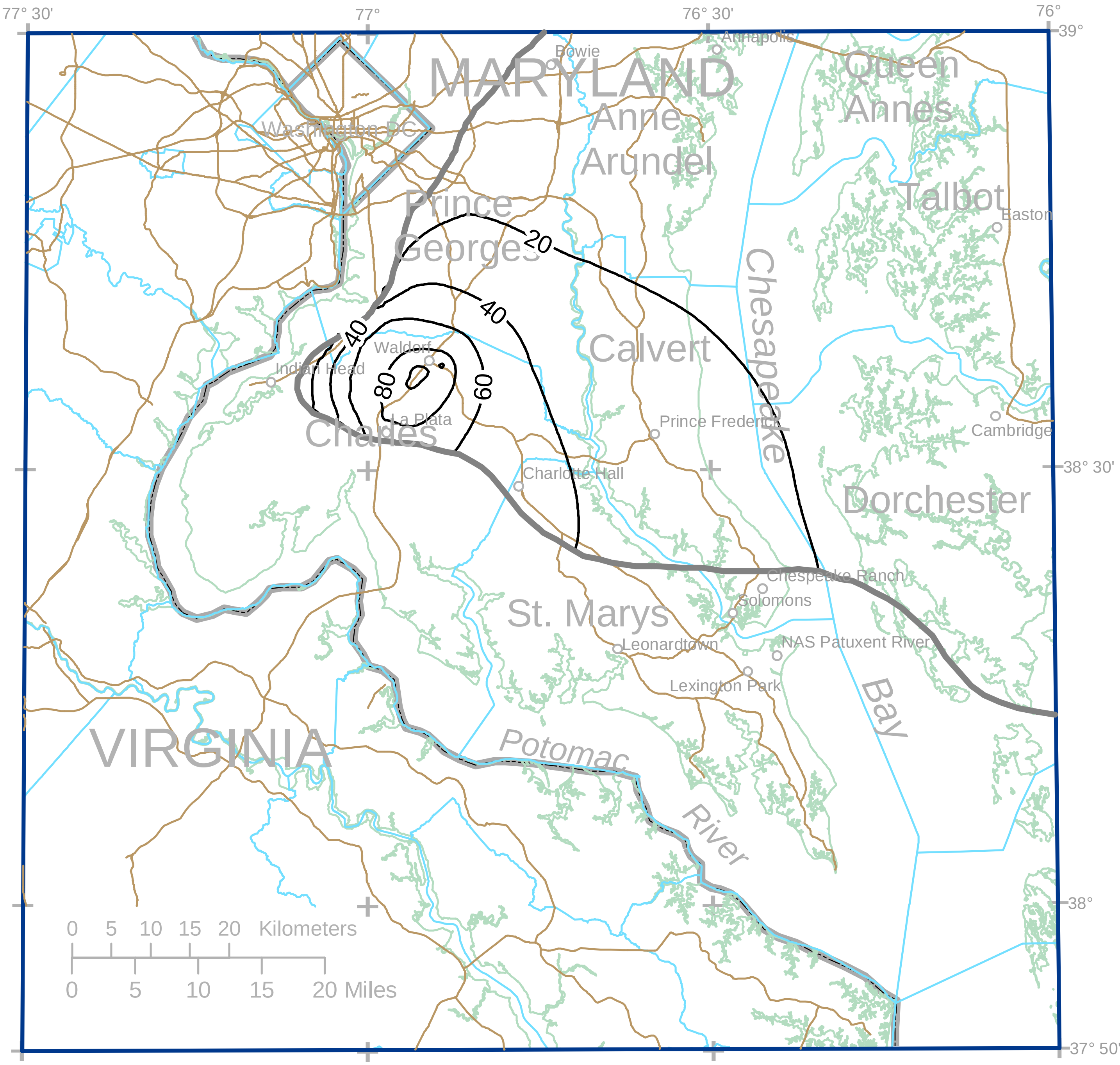


Explanation

Contour of simulated drawdown, in feet

Approximate extent of the Aquia aquifer

Figure 10b. Simulated drawdown in the Aquia aquifer, 2002 to 2030, based on Scenario 1.

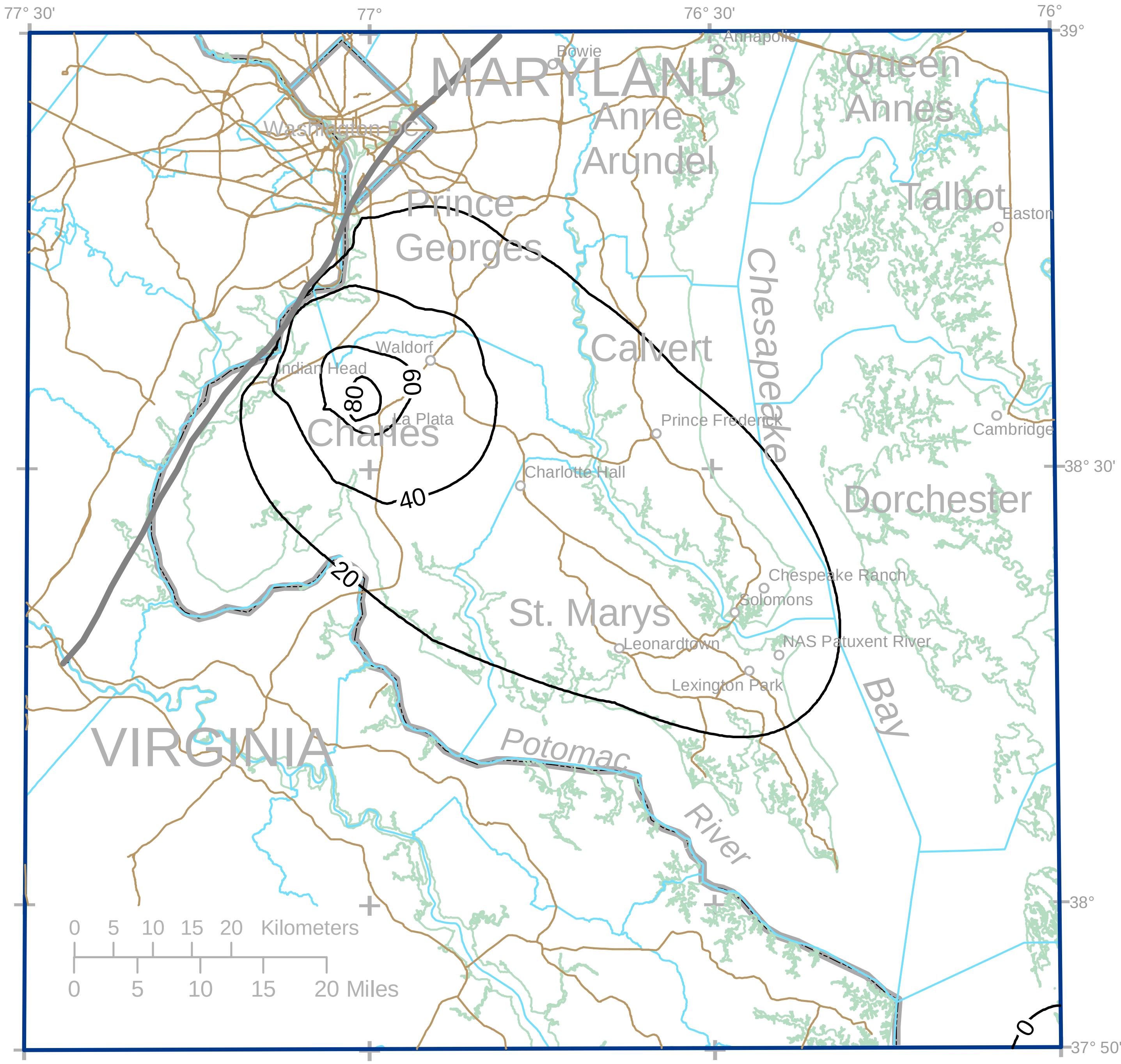


Explanation

Contour of simulated drawdown, in feet

Approximate extent of the Magothy aquifer

Figure 10c. Simulated drawdown in the Magothy aquifer, 2002 to 2030, based on Scenario 1.

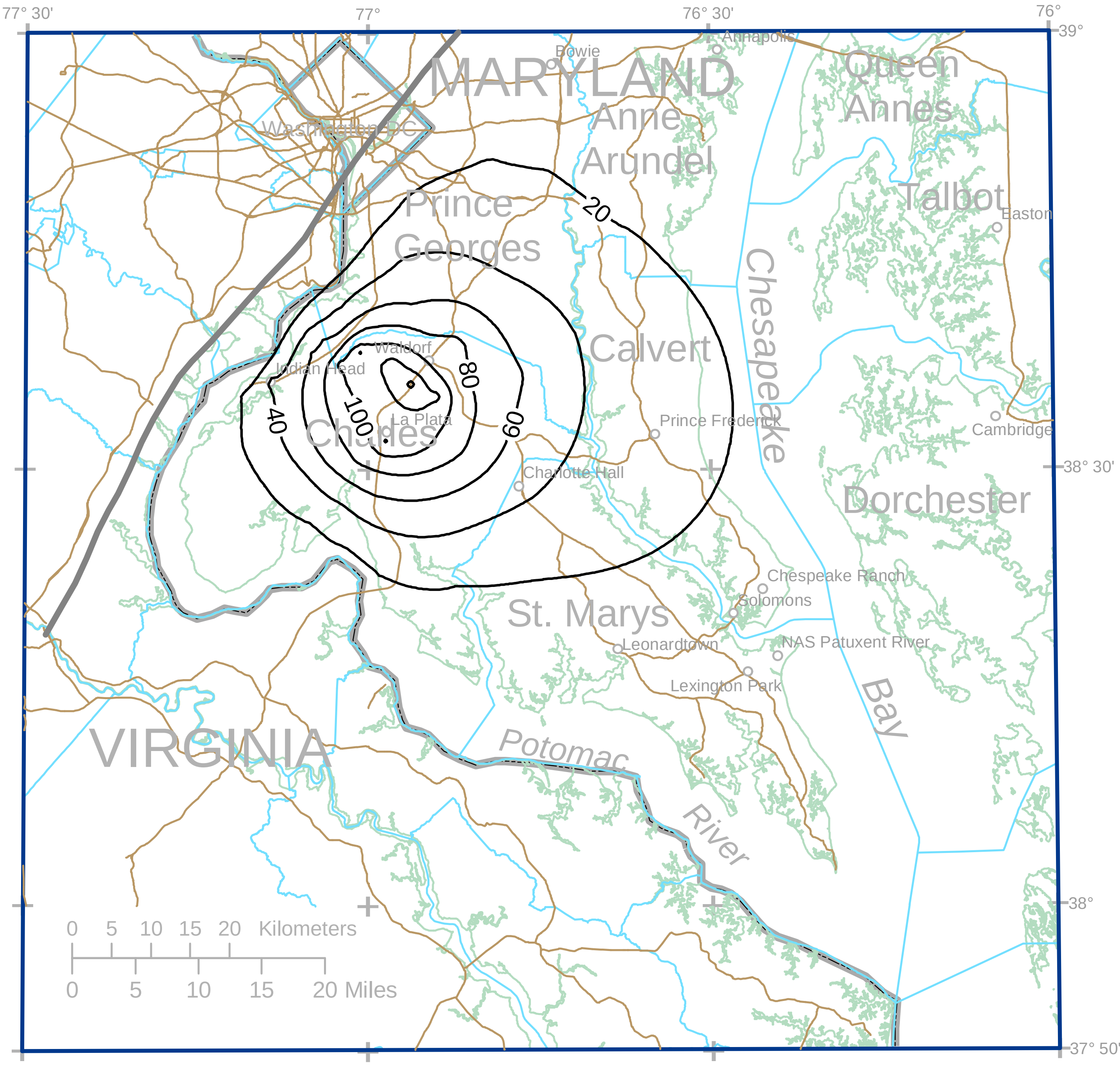


Explanation

Contour of simulated drawdown, in feet

Approximate extent of the Upper Patapsco aquifer

Figure 10d. Simulated drawdown in the Upper Patapsco aquifer, 2002 to 2030, based on Scenario 1.

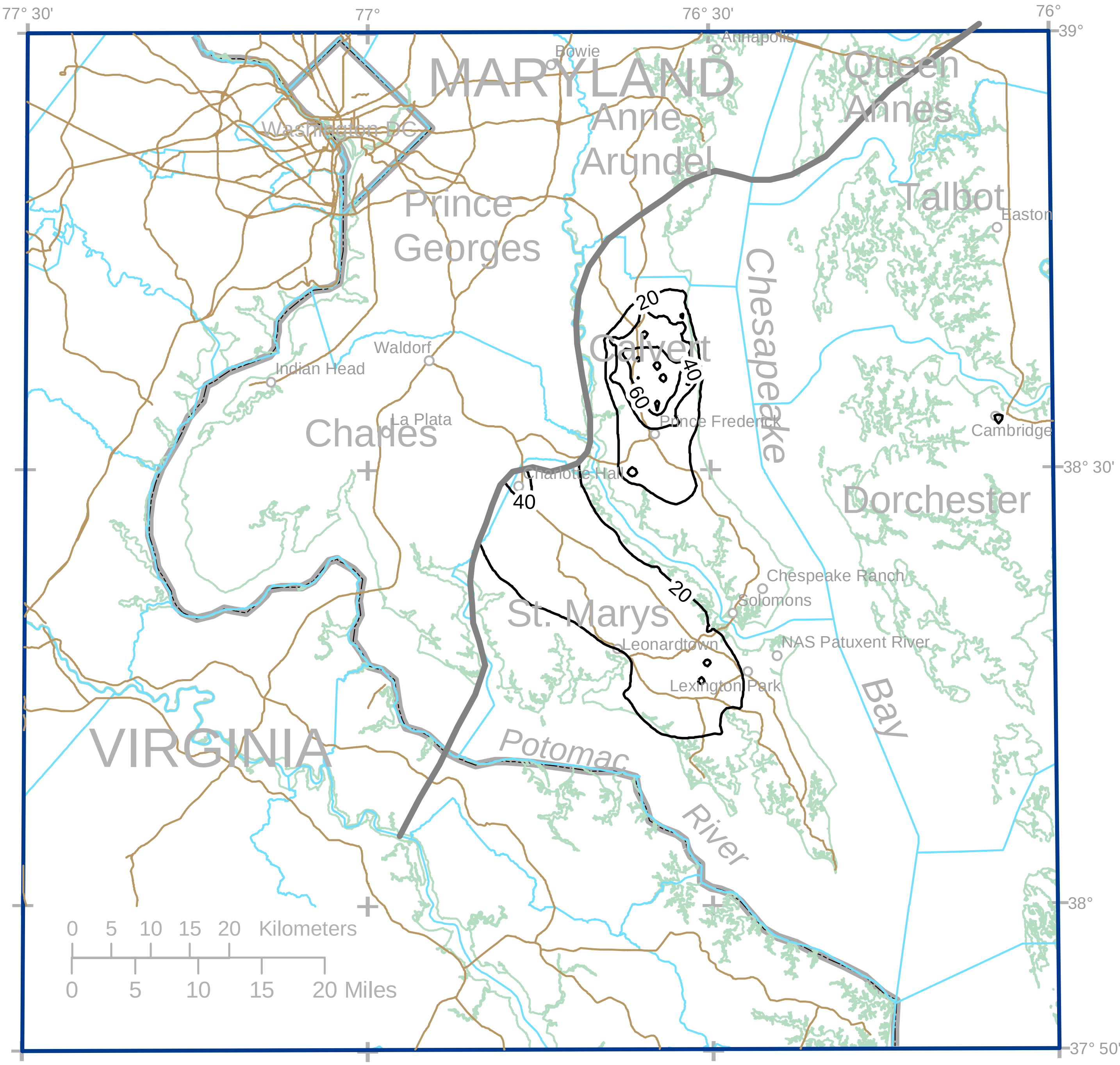


Explanation

Contour of simulated drawdown, in feet

Approximate extent of the Lower Patapsco aquifer

Figure 10e. Simulated drawdown in the Lower Patapsco aquifer, 2002 to 2030, based on Scenario 1.



Explanation

Contour of simulated drawdown, in feet

Approximate extent of the Piney Point aquifer

Figure 11a. Simulated drawdown in the Piney Point aquifer, 2002 to 2030, based on Scenario 2b.

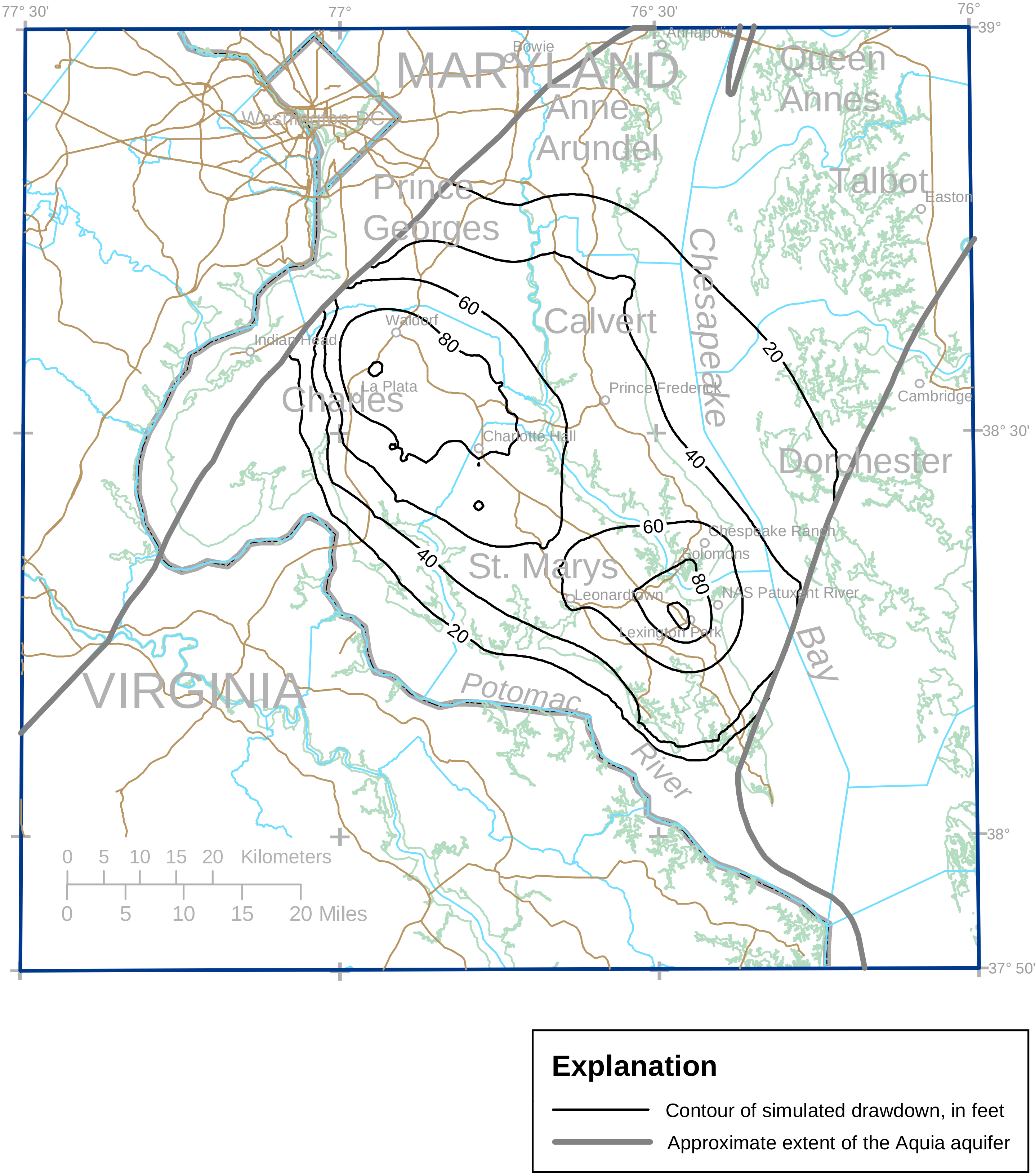


Figure 11b. Simulated drawdown in the Aquia aquifer, 2002 to 2030, based on Scenario 2b.

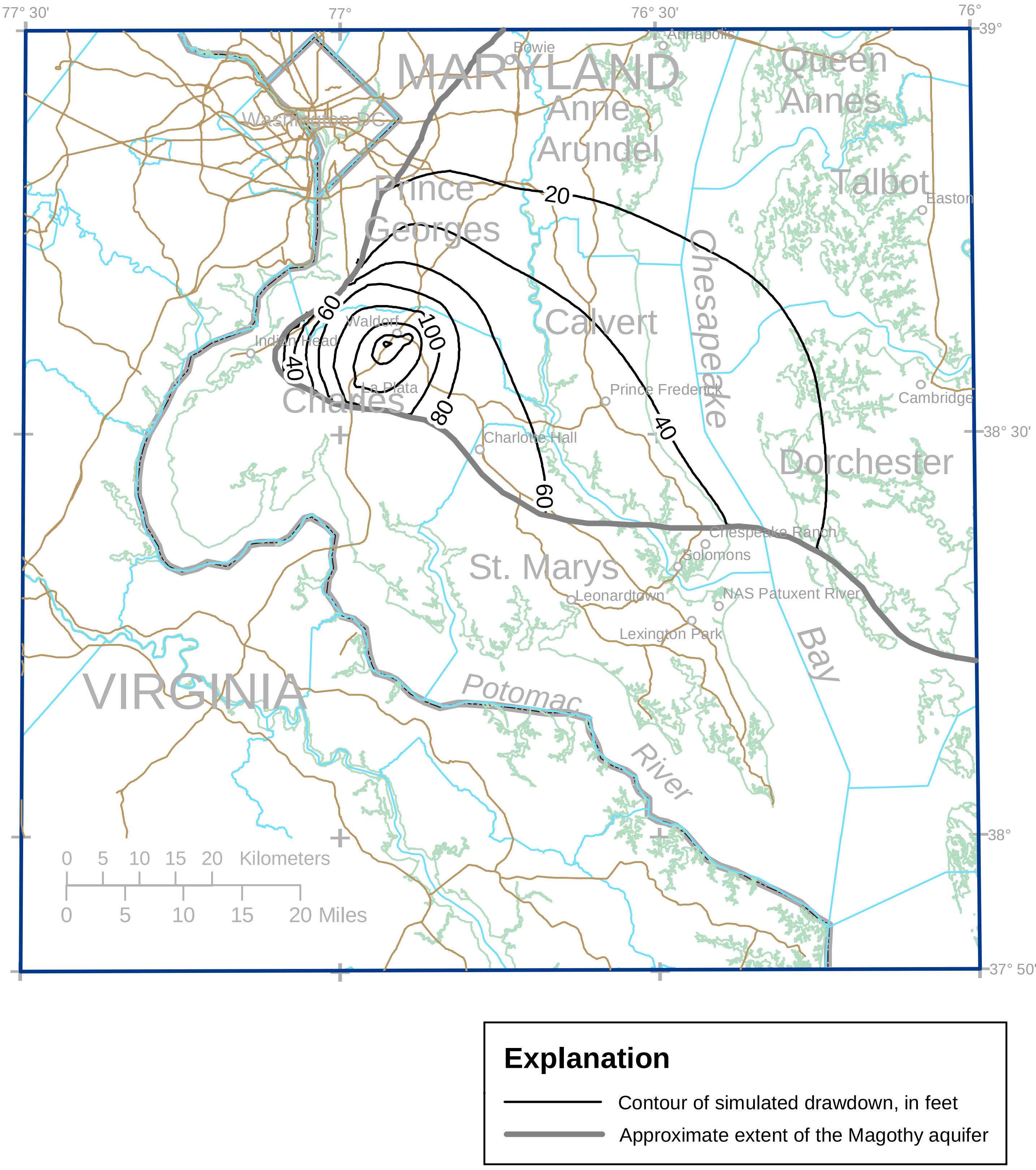
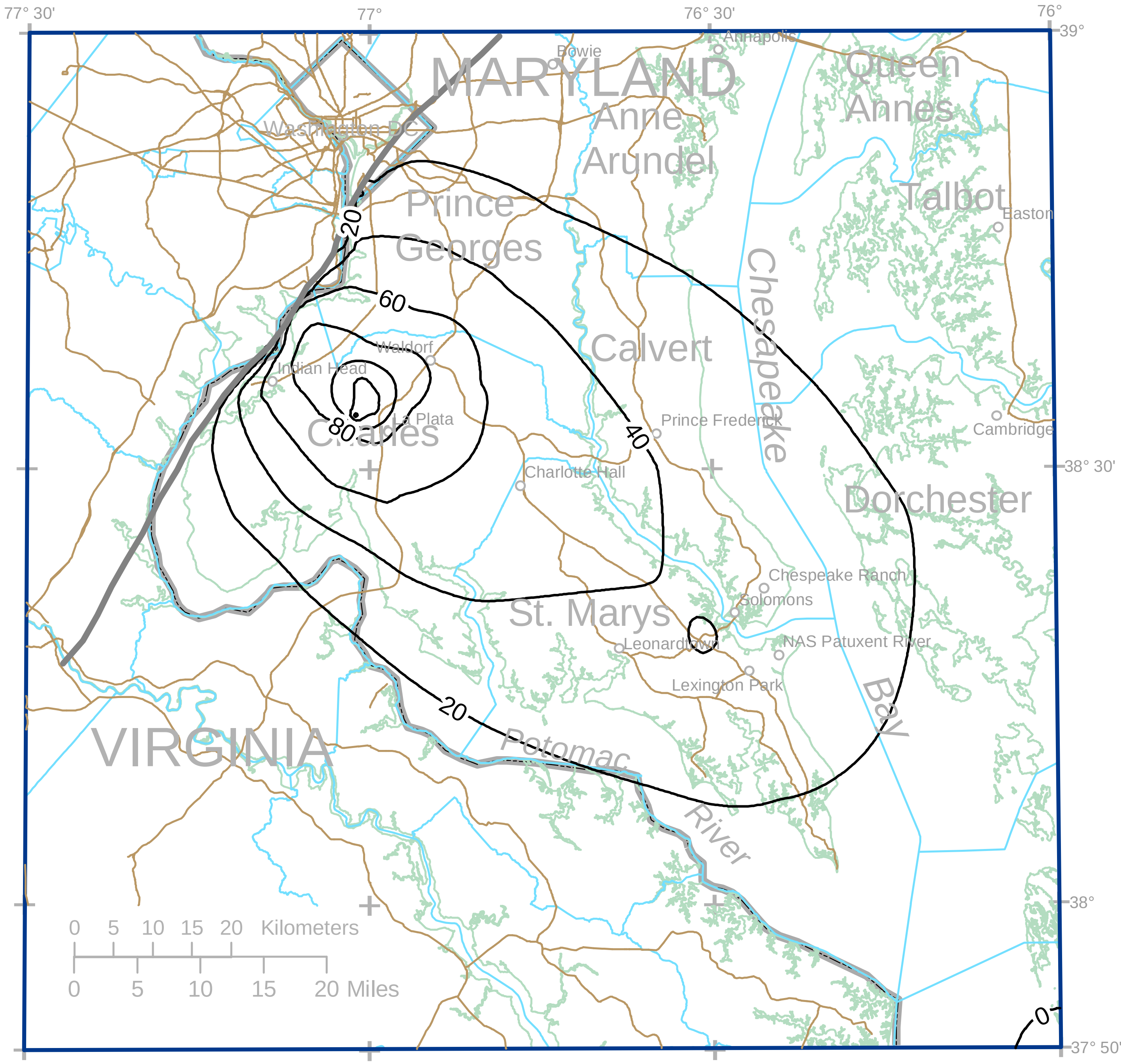


Figure 11c. Simulated drawdown in the Magothy aquifer, 2002 to 2030, based on Scenario 2b.

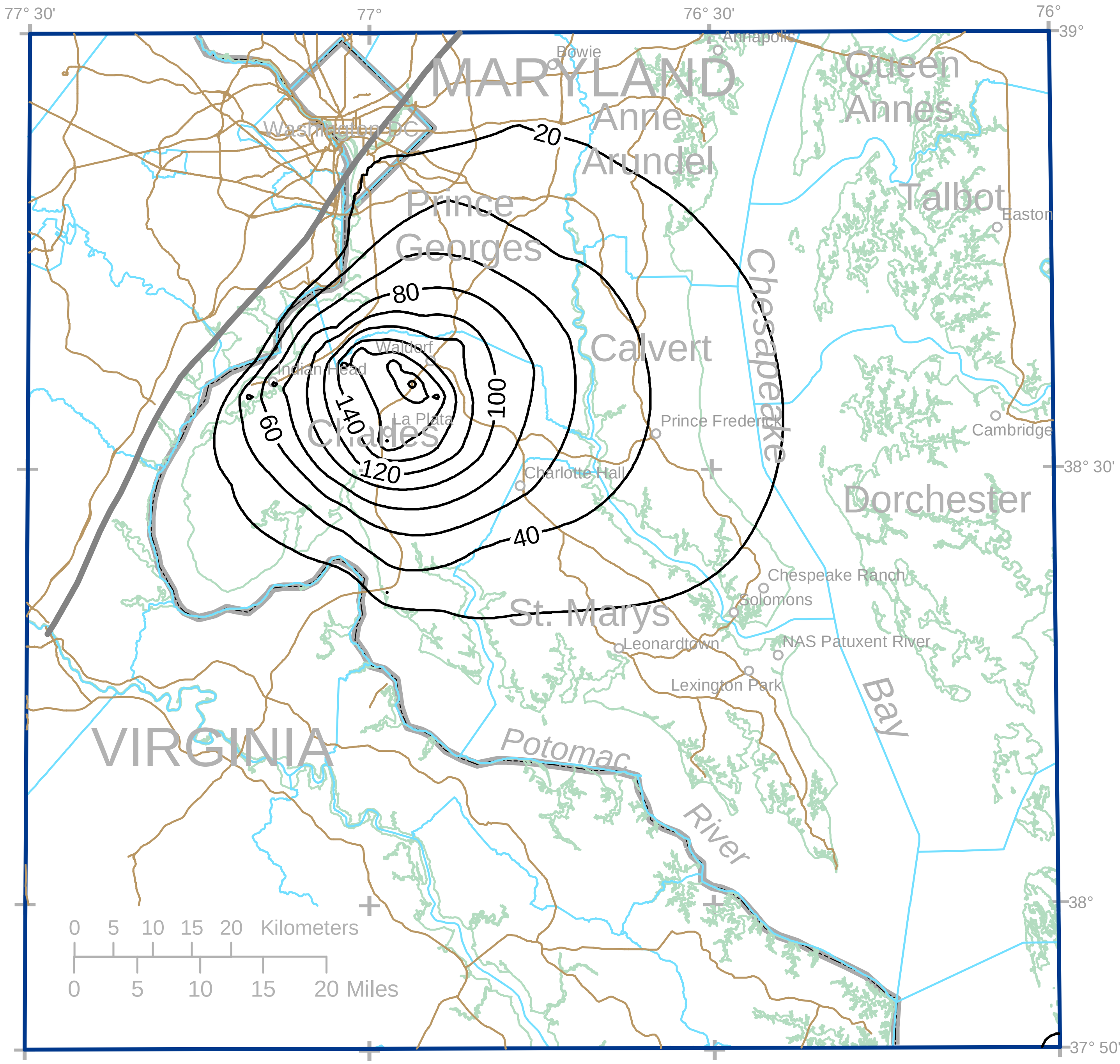


Explanation

Contour of simulated drawdown, in feet

Approximate extent of the Upper Patapsco aquifer

Figure 11d. Simulated drawdown in the Upper Patapsco aquifer, 2002 to 2030, based on Scenario 2b.



Explanation

Contour of simulated drawdown, in feet

Approximate extent of the Lower Patapsco aquifer

Figure 11e. Simulated drawdown in the Lower Patapsco aquifer, 2002 to 2030, based on Scenario 2b.

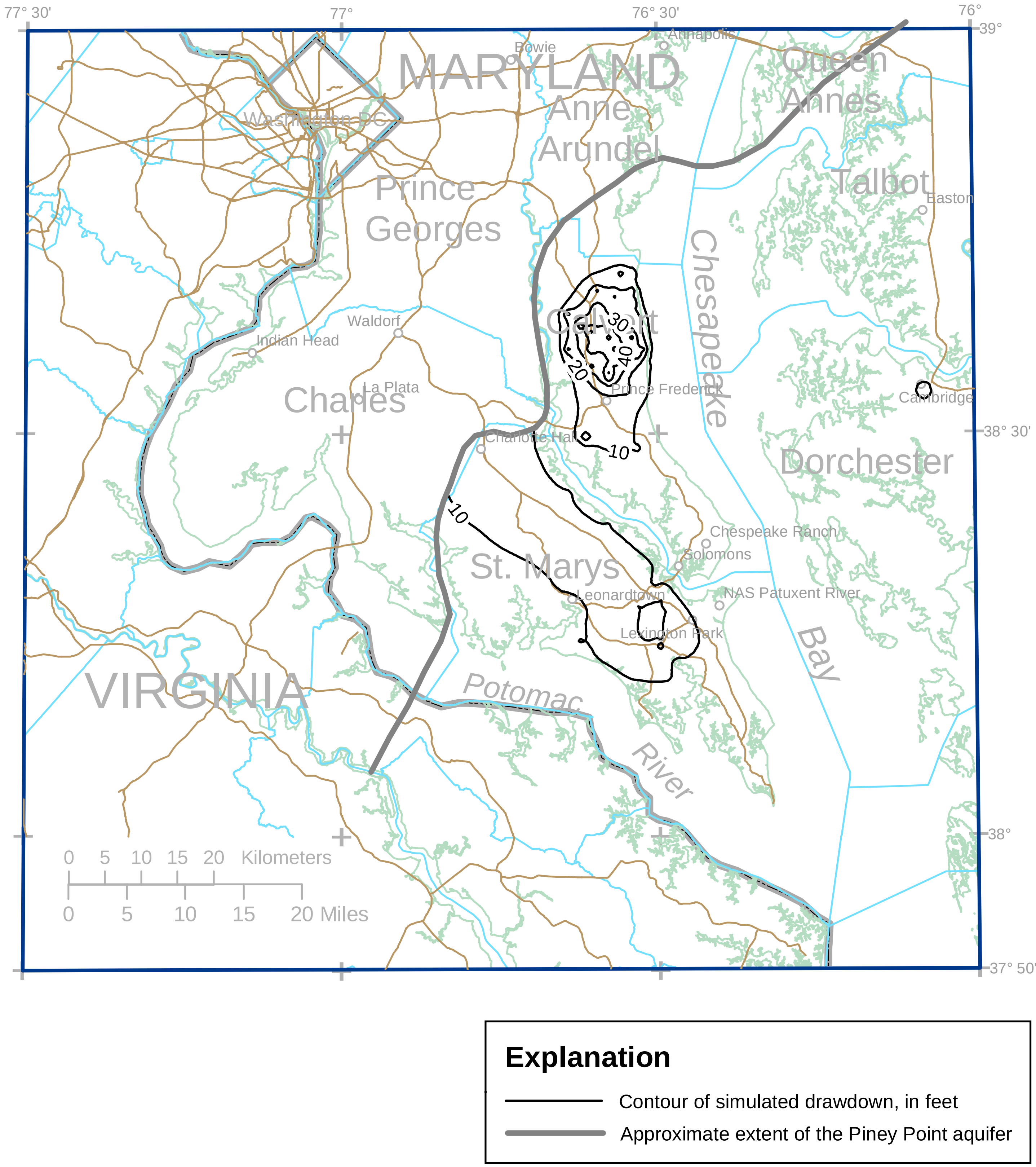


Figure 12a. Simulated drawdown in the Piney Point aquifer, 2002 to 2030, based on Scenario 5b.

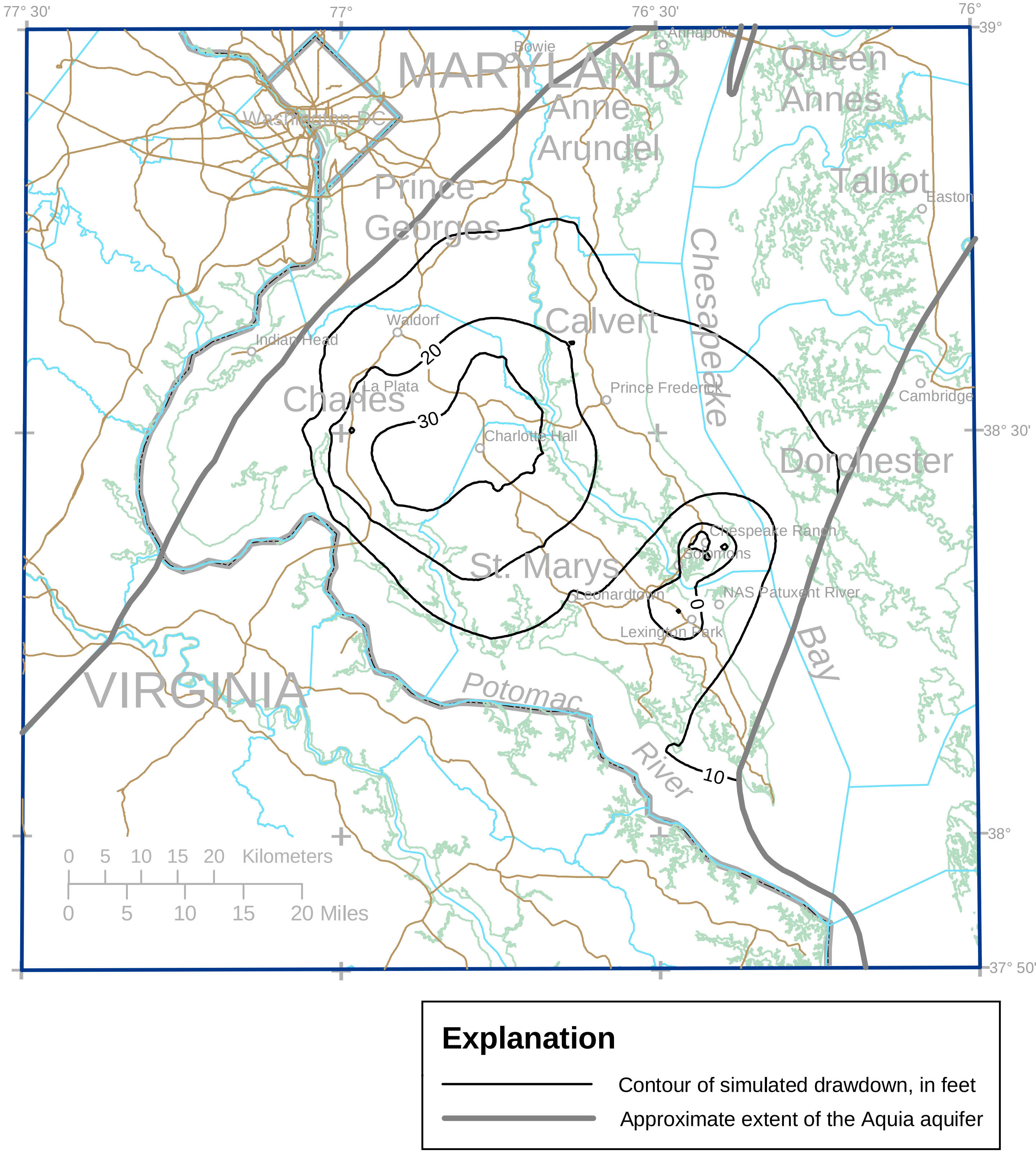


Figure 12b. Simulated drawdown in the Aquia aquifer, 2002 to 2030, based on Scenario 5b.

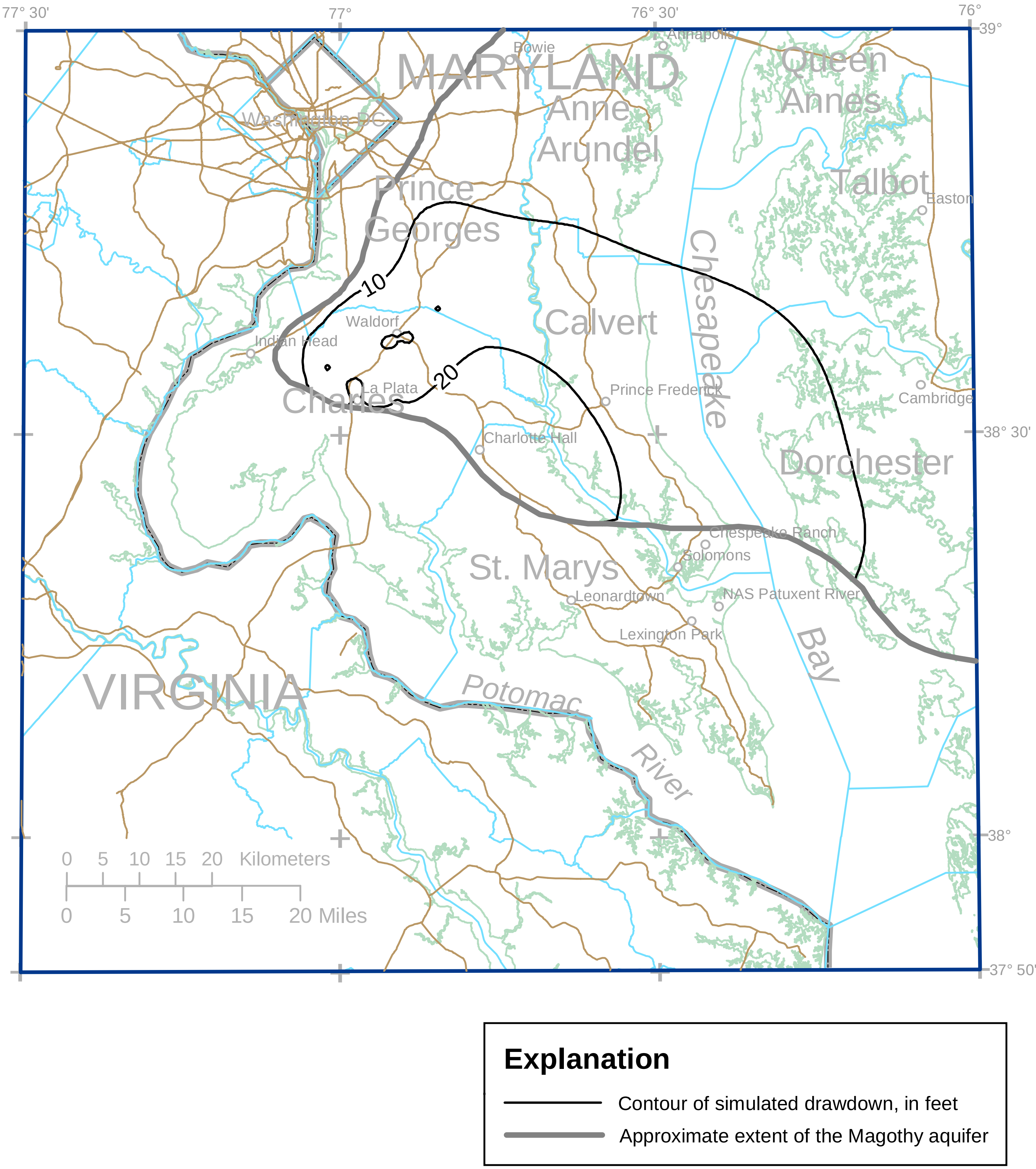
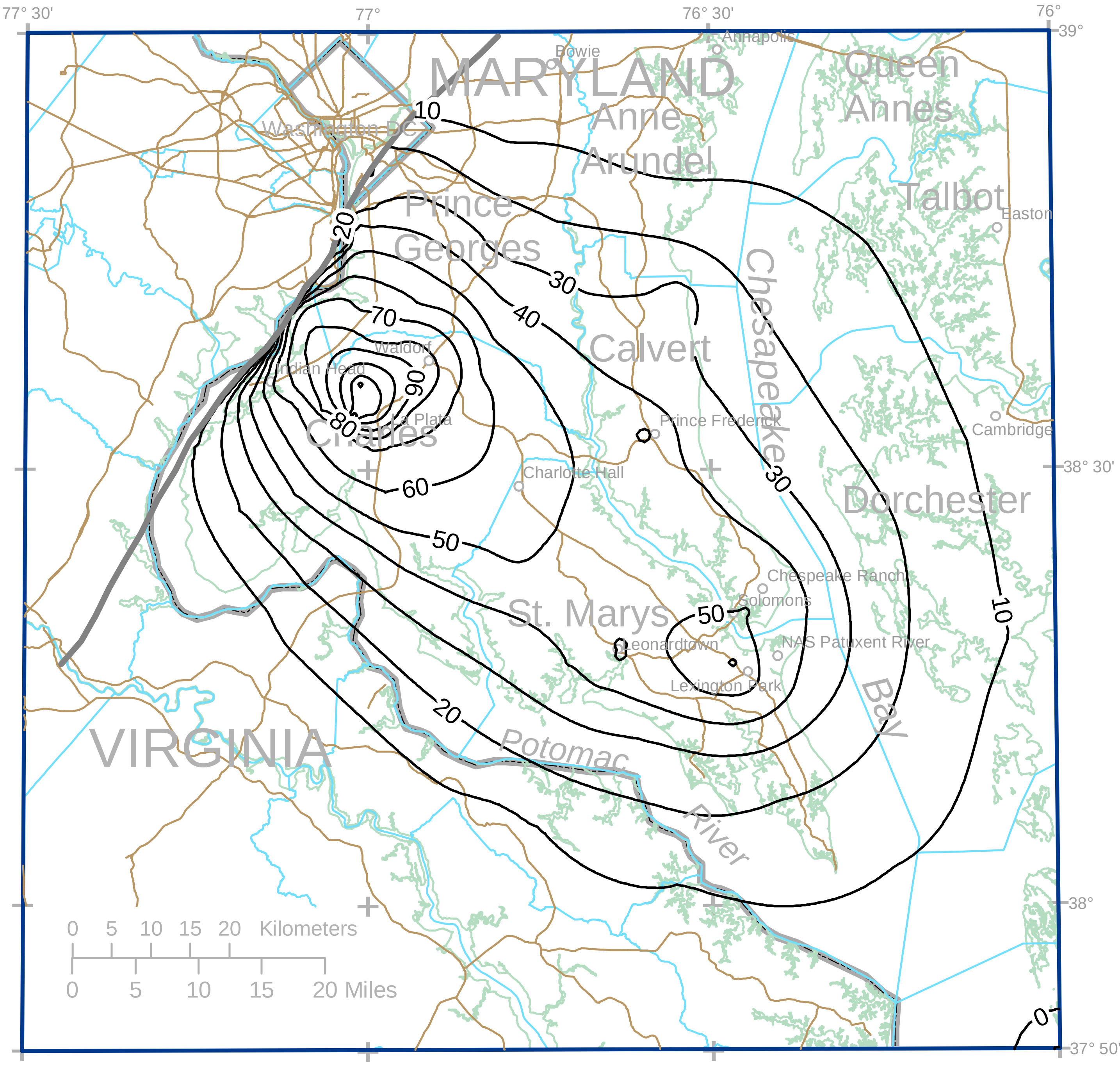


Figure 12c. Simulated drawdown in the Magothy aquifer, 2002 to 2030, based on Scenario 5b.

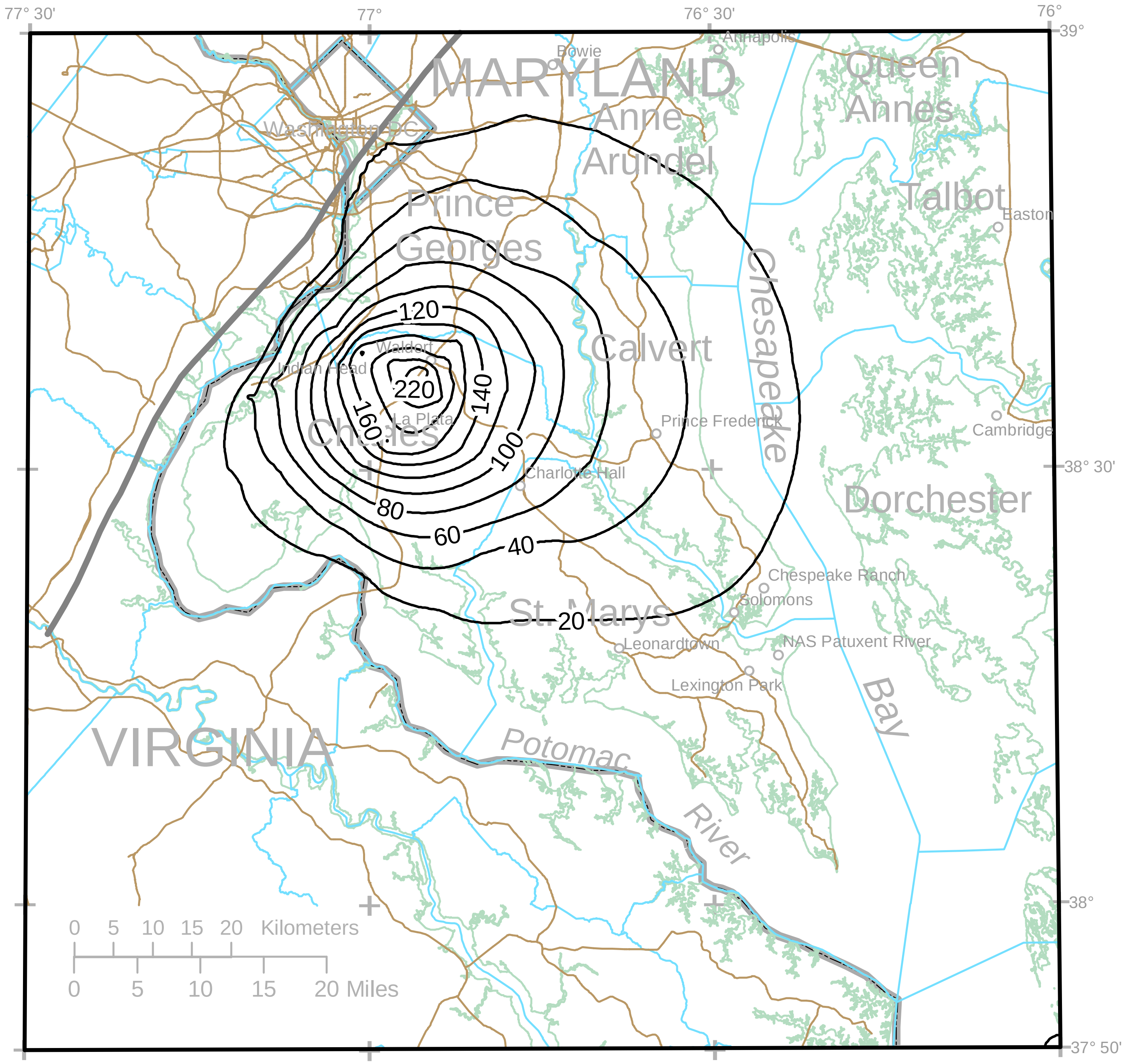


Explanation

Contour of simulated drawdown, in feet

Approximate extent of the Upper Patapsco aquifer

Figure 12d. Simulated drawdown in the Upper Patapsco aquifer, 2002 to 2030, based on Scenario 5b.



Explanation

Contour of simulated drawdown, in feet

Approximate extent of the Lower Patapsco aquifer

Figure 12e. Simulated drawdown in the Lower Patapsco aquifer, 2002 to 2030, based on Scenario 5b.

Table 1. Geologic and hydrostratigraphic units of Southern Maryland
[Modified from Achmad and Hansen, 1997]

ERATHEM	SYSTEM	SERIES	GROUP	FORMATION	THICKNESS (feet)	LITHOLOGY	HYDROSTRATIGRAPHIC UNIT
CENOZOIC	QUATERNARY	Holocene & Pleistocene		Lowland deposits	0-150	Sand, gravel, sandy clay, and clay.	SURFICIAL AQUIFER
	NEOGENE	Pliocene		Upland deposits	0-85	Irregularly stratified cobbles, gravel, sand, and clay lenses.	
			Chesapeake Group	Yorktown Fm.	0-20	Fine-grained glauconitic sand.	CHESAPEAKE CONFINING UNIT
		Miocene		Eastover Fm.	0.5-40	Clayey silt with thin laminae of silt, clay, or sand.	
				St. Marys Fm.	0-335	Sand, clayey sand, and sandy clay; fossiliferous and diatomaceous.	
				Choptank Fm.			
				Calvert Fm.			
	PALEOGENE	Oligocene		Old Church Fm.	0-5	Patchy distribution; clayey, glauconitic sand.	PINEY POINT AQUIFER
		Eocene	Pamunkey Group	Piney Point Fm.	0-90	Sand, slightly glauconitic, with intercalated indurated layers; fossiliferous.	
				Nanjemoy Fm.	0-240	Glauconitic sand with clayey layers.	NANJEMOY CONFINING UNIT
		Paleocene		Marlboro Clay	0-30	Pink and gray clay.	
				Aquia Fm.	30-205	Glauconitic, greenish to brown sand with indurated layers; fossiliferous.	AQUIA AQUIFER
				Brightseat Fm.	0-40	Gray to dark-gray micaceous silty and sandy clay.	BRIGHTSEAT CONFINING UNIT
MESOZOIC	CRETACEOUS	Upper	Monmouth Group Matawan Group	Formations undifferentiated	0-135	Sandy clay and sand, dark gray to black, with minor glauconite; fossiliferous.	
				Magothy Fm.	0-230	Light gray to white sand and fine gravel with interbedded clay layers; contains pyrite and lignite. Includes two sand units in southern Anne Arundel County where the formation is thickest.	MAGOTHY AQUIFER
		Lower	Potomac Group	Patapsco Fm.	0-1,200	Interbedded sand, clay, and sandy clay; color variegated, but chiefly hues of red, brown and gray; consists of several sandy intervals that function as separate aquifers.	Patapsco aquifer system: UPPER PATAPSCO CONFINING UNIT UPPER PATAPSCO AQUIFER MIDDLE PATAPSCO CONFINING UNIT LOWER PATAPSCO AQUIFER
				Arundel Fm.	0-400	Red, brown, and gray clay; in places contains ironstone nodules, carbonaceous remains, and lignite.	ARUNDEL CONFINING UNIT
				Patuxent Fm.	100-650	Interbedded gray and yellow sand and clay; kaolinized feldspar and lignite common. Locally clay layers predominate.	PATUXENT AQUIFER
PALEOZOIC PRECAMBRIAN	Undifferentiated pre-Cretaceous consolidated-rock basement				Unknown	Igneous and metamorphic rocks; sandstone and shale.	NOT RECOGNIZED

Table 2. Construction and yield characteristics of the six test wells

[deg, degree; min, minute; sec, second; ft, feet; gal/min, gallons per minute; (gal/min)/ft, gallons per minute per foot]

Well number	State permit number	Location	Latitude Longitude (deg min sec)	Driller	Date completed	Altitude of land surface (ft above sea level)	Depth of hole (ft below land surface)
CA Db 96	CA-94-4191	Prince Frederick	38 32 44 76 35 42	A.C. Schultes of Md.	12/12/2002	151.56	1,660
CA Fd 85	CA-94-3305	Chesapeake Ranch Estates	38 22 36 76 25 54	Sydnor Hydrodynamics	11/14/2001	105.98	1,664
CH Bg 17	CH-94-5325	Malcolm	38 37 06 76 47 54	A.C. Schultes of Md.	3/3/2003	199.16	1,660
CH Cg 24	CH-94-4194	Hughesville	38 32 54 76 48 14	Sydnor Hydrodynamics	1/16/2002	171.04	1,667
SM Bc 39	SM-94-3921	Persimmon Hills	38 26 05 76 43 02	Sydnor Hydrodynamics	3/18/2002	161.54	1,600
SM Dd 72	SM-94-3616	Paw Paw Hollow	38 16 26 76 39 34	A.C. Schultes of Md.	5/16/2001	109.99	1,650

Well number	Depth of well (ft below land surface)	Screened intervals (ft below land surface)	Aquifer	Pumping test			
				Discharge (gal/min)	Static level (ft below land surface)	Drawdown at 24 hours (ft below land surface)	Specific capacity ((gal/min)/ft)
CA Db 96	970	930-960	Upper Patapsco	73.2	190.66	35.49	2.06
CA Fd 85	1,643	1,535-1,545 1,560-1,570 1,623-1,633	Lower Patapsco	82.5	120.51	18.24	4.52
CH Bg 17	1,353	1,299-1,314 1,328-1,343	Lower Patapsco	60.4	253.21	39.98	1.51
CH Cg 24	835	795-825	Upper Patapsco	56.3	219.25	33.90	1.66
SM Bc 39	1,542	1,492-1,512 1,522-1,532	Lower Patapsco	66.3	190.61	35.72	1.86
SM Dd 72	1,340	1,300-1,330	Lower Patapsco	70.0	131.00	28.51	2.46

Table 3. Historical population of Calvert, Charles, and St. Mary's Counties

Historical population										
County	1950[1]	1952[2]	1960[1]	1970[1]	1980[1]	1982[3]	1990[1]	1994[4]	2000[5]	2002[5]
Calvert	12,100	12,845	15,826	20,682	34,638	36,225	51,372	60,046	74,563	80,906
Charles	23,415	25,246	32,572	47,678	72,751	77,897	101,154	109,039	120,546	129,040
St. Mary's	29,111	31,072	38,915	47,388	59,895	61,697	75,974	79,998	86,211	90,044
Total	64,626	69,163	87,313	115,748	167,284	175,819	228,500	251,083	281,320	299,990

Population as a fraction of 2002 population										
County	1950	1952	1960	1970	1980	1982	1990	1994	2000	2002
Calvert	0.150	0.159	0.196	0.256	0.428	0.448	0.635	0.767	0.922	1.000
Charles	0.181	0.196	0.252	0.369	0.564	0.604	0.784	0.845	0.934	1.000
St. Mary's	0.323	0.345	0.432	0.526	0.665	0.685	0.844	0.888	0.957	1.000

Sources of population data:
[1] U.S. Census Bureau, 1995
[2] Interpolated from 1950 and 1960 data
[3] U.S. Census Bureau, 1992
[4] U.S. Census Bureau, 2000
[5] U.S. Census Bureau, 2003

Table 4. Projected population of Calvert, Charles, and St. Mary's Counties

CALVERT Election District	Census population 2000	Estimated population 2002	Projected population 2010	Projected population 2020	Projected population 2030	Fraction of 2002 population 2010	2020	2030
1	29,552	32,066	32,995	34,387	35,686	1.03	1.07	1.11
2	22,769	24,706	29,311	31,433	33,162	1.19	1.27	1.34
3	22,242	24,134	28,695	30,180	31,152	1.19	1.25	1.29
Total	**74,563**	**80,906**	**91,000**	**96,000**	**100,000**	**1.12**	**1.19**	**1.24**

CHARLES Election District	Census population 2000	Estimated population 2002	Projected population 2010	Projected population 2020	Projected population 2030	Fraction of 2002 population 2010	2020	2030
1	11,997	12,842	13,732	15,152	16,606	1.07	1.18	1.29
2	1,912	2,047	2,119	2,325	2,553	1.04	1.14	1.25
3	3,169	3,392	3,376	3,579	3,853	1.00	1.06	1.14
4	4,774	5,110	5,837	7,851	9,846	1.14	1.54	1.93
5	3,682	3,941	3,958	4,209	4,509	1.00	1.07	1.14
6	62,532	66,938	82,192	107,996	120,145	1.23	1.61	1.79
7	11,859	12,695	12,564	14,379	16,329	0.99	1.13	1.29
8	12,603	13,491	13,236	14,956	16,912	0.98	1.11	1.25
9	4,784	5,121	7,017	8,970	10,431	1.37	1.75	2.04
10	3,234	3,462	3,369	3,583	3,816	0.97	1.03	1.10
Total	**120,546**	**129,040**	**147,400**	**183,000**	**205,000**	**1.14**	**1.42**	**1.59**

ST. MARY'S Election District	Census population 2000	Estimated population 2002	Projected population 2010	Projected population 2020	Projected population 2030	Fraction of 2002 population 2010	2020	2030
1	5,664	5,916	6,550	7,055	7,695	1.11	1.19	1.30
2	6,074	6,344	6,638	7,629	8,518	1.05	1.20	1.34
3	10,785	11,265	13,109	14,663	16,219	1.16	1.30	1.44
4	8,819	9,211	10,579	12,148	13,535	1.15	1.32	1.47
5	10,677	11,152	12,420	14,882	17,566	1.11	1.33	1.58
6	10,704	11,180	12,016	13,626	15,081	1.07	1.22	1.35
7	3,136	3,275	3,607	3,863	4,136	1.10	1.18	1.26
8	30,084	31,422	35,592	40,599	44,453	1.13	1.29	1.41
9	268	280	289	335	397	1.03	1.20	1.42
Total	**86,211**	**90,044**	**100,800**	**114,800**	**127,600**	**1.12**	**1.27**	**1.42**

Table 5. Historical pumpage totals used in the ground-water-flow model

	Pumpage, in million gallons per day			
	1901-1952	1953-1982	1983-1994	1995-2002
Calvert County				
Domestic	0.46	1.28	2.20	2.87
Major Users	0.59	1.06	2.13	3.36
Total	1.04	2.35	4.32	6.23
Charles County				
Domestic	0.55	1.68	2.36	2.79
Major Users	1.12	4.93	8.43	9.02
Total	1.66	6.61	10.78	11.80
St. Mary's County				
Domestic	0.92	1.83	2.37	2.67
Major Users	1.94	3.22	4.57	5.29
Total	2.86	5.04	6.93	7.96
Other Counties*				
Major Users	8.65	13.61	16.70	17.44
Total	14.22	27.61	38.75	43.43

*Within the model area

Discrepancies due to rounding

Table 6a. Simulated pumpage 2003-2010, in million gallons per day

	Simulation number											
	1	2a	2b	3a	3b	4	5a	5b	6	7a	7b	8
Calvert County												
Domestic	3.55	3.90	4.26	3.19	2.84	3.55	3.55	3.55	3.55	3.55	3.55	3.55
Hypothetical	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.50
Major user	3.65	4.02	4.38	3.29	2.92	3.53	3.65	3.65	3.65	3.65	3.65	3.65
Total	7.20	7.92	8.64	6.48	5.76	7.08	7.20	7.20	7.70	7.20	7.20	7.70
Charles County												
Domestic	3.35	3.68	4.02	3.01	2.68	3.35	3.35	3.35	3.35	3.35	3.35	3.35
Hypothetical	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.75
Major user	10.27	11.30	12.33	9.25	8.22	10.00	10.27	10.27	10.27	10.27	10.27	10.27
Total	13.62	14.98	16.35	12.26	10.90	13.35	13.62	13.62	14.62	13.62	13.62	14.37
St. Mary's County												
Domestic	3.09	3.39	3.70	2.78	2.47	3.09	3.09	3.09	3.09	3.09	3.09	3.09
Hypothetical	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.92
Major user	5.87	6.45	7.04	5.28	4.69	5.55	5.87	5.87	5.87	5.89	5.91	5.87
Total	8.95	9.85	10.74	8.06	7.16	8.63	8.95	8.95	9.15	8.97	9.00	9.87
Other counties												
Major user	17.44	17.44	17.44	17.44	17.44	17.44	17.44	17.44	17.44	17.44	17.44	17.44
Total	**47.22**	**50.20**	**53.18**	**44.24**	**41.27**	**46.50**	**47.22**	**47.22**	**48.92**	**47.24**	**47.26**	**49.39**

Discrepancies due to rounding

Table 6b. Simulated pumpage 2011-2020, in million gallons per day

	Simulation number											
	1	2a	2b	3a	3b	4	5a	5b	6	7a	7b	8
Calvert County												
Domestic	3.75	4.13	4.50	3.38	3.00	3.75	3.75	3.75	3.75	3.75	3.75	3.75
Hypothetical	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.50
Major user	3.81	4.19	4.57	3.43	3.05	3.73	3.81	3.81	3.81	3.81	3.81	3.81
Total	7.56	8.32	9.07	6.80	6.05	7.49	7.56	7.56	8.06	7.56	7.56	8.06
Charles County												
Domestic	4.04	4.44	4.85	3.63	3.23	4.04	4.04	4.04	4.04	4.04	4.04	4.04
Hypothetical	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.75
Major user	12.58	13.84	15.10	11.33	10.07	11.26	12.57	12.56	12.58	12.58	12.58	12.58
Total	16.62	18.28	19.95	14.96	13.30	15.30	16.61	16.60	17.62	16.62	16.62	17.37
St. Mary's County												
Domestic	3.52	3.87	4.22	3.17	2.81	3.52	3.52	3.52	3.52	3.52	3.52	3.52
Hypothetical	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.92
Major user	6.55	7.20	7.86	5.89	5.24	5.87	6.55	6.55	6.55	6.60	6.64	6.55
Total	10.07	11.07	12.08	9.06	8.05	9.39	10.07	10.07	10.27	10.11	10.16	10.99
Other counties												
Major user	17.44	17.44	17.44	17.44	17.44	17.44	17.44	17.44	17.44	17.44	17.44	17.44
Total	**51.69**	**55.12**	**58.54**	**48.27**	**44.84**	**49.62**	**51.68**	**51.67**	**53.39**	**51.74**	**51.79**	**53.86**

Discrepancies due to rounding

Table 6c. Simulated pumpage 2021-2030, in million gallons per day

	Simulation number											
	1	2a	2b	3a	3b	4	5a	5b	6	7a	7b	8
Calvert County												
Domestic	3.91	4.31	4.70	3.52	3.13	3.91	3.91	3.91	3.91	3.91	3.91	3.91
Hypothetical	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.00	0.00	0.50
Major user	3.93	4.32	4.72	3.54	3.14	3.94	3.93	3.93	3.93	3.93	3.93	3.93
Total	7.84	8.63	9.41	7.06	6.28	7.86	7.84	7.84	8.34	7.84	7.84	8.34
Charles County												
Domestic	4.61	5.07	5.53	4.15	3.69	4.61	4.61	4.61	4.61	4.61	4.61	4.61
Hypothetical	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.75
Major user	13.83	15.22	16.60	12.45	11.07	12.54	13.82	13.81	13.83	13.83	13.83	13.83
Total	18.45	20.29	22.14	16.60	14.76	17.16	18.43	18.42	19.45	18.45	18.45	19.20
St. Mary's County												
Domestic	3.94	4.33	4.73	3.55	3.15	3.94	3.94	3.94	3.94	3.94	3.94	3.94
Hypothetical	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.92
Major user	7.12	7.83	8.54	6.41	5.70	6.20	7.12	7.12	7.12	7.19	7.27	7.12
Total	11.06	12.16	13.27	9.95	8.85	10.14	11.06	11.06	11.26	11.13	11.21	11.98
Other counties												
Major user	17.44	17.44	17.44	17.44	17.44	17.44	17.44	17.44	17.44	17.44	17.44	17.44
Total	**54.79**	**58.53**	**62.26**	**51.06**	**47.32**	**52.59**	**54.78**	**54.77**	**56.49**	**54.87**	**54.94**	**56.96**

Discrepancies due to rounding

Table 7a. Summary of critical-location information

Map ID[1]	GAP or identifier	Aquifer	Location	Prepumping head	Altitude of aquifer top	Management level
Calvert County						
1	CA60G002	Aquia	Chesapeake Ranch	12.5	-456.9	-363.0
2	CA60G002	Upper Patapsco	Chesapeake Ranch	18.6	-625.4	-496.6
3	CA74G005	Aquia	Prince Frederick	19.4	-333.0	-262.6
4	CA84G003	Aquia	Solomons	13.3	-451.8	-358.8
5	CA84G003	Upper Patapsco	Solomons	18.4	-595.5	-472.7
6	Domestic observation	Aquia	Huntingtown	20.3	-292.3	-229.8
7	Hypothetical major user	Lower Patapsco	Huntingtown	33.4	-1,169.1	-928.6
8	Hypothetical public supply	Upper Patapsco	Prince Frederick	22.5	-667.0	-537.1
9	Hypothetical public supply	Upper Patapsco	Solomons	18.4	-594.0	-471.6
Charles County						
10	CH68G001	Upper Patapsco	La Plata	32.9	-264.0	-204.6
11	CH70G003	Lower Patapsco	La Plata	31.5	-725.1	-573.8
12	CH70G109	Magothy	Waldorf	53.8	-234.6	-176.9
13	CH71G005	Lower Patapsco	Indian Head	20.1	-166.3	-129.0
14	CH83G312	Lower Patapsco	Waldorf	33.4	-751.3	-594.4
15	CH89G032	Lower Patapsco	Bensville	30.9	-507.7	-400.0
16	Hypothetical major user	Lower Patapsco	Billingsly Road	33.2	-874.6	-693.0
17	Hypothetical public supply	Lower Patapsco	Waldorf Fire Station	34.6	-802.9	-635.4
18	Hypothetical public supply	Lower Patapsco	Barrington Drive	33.9	-810.9	-641.9
St. Mary's County						
19	SM46G001	Aquia	Lexington Park Pegg Rd	13.2	-449.1	-356.6
20	SM46G001	Upper Patapsco	Lexington Park Pegg Rd	18.1	-572.0	-453.9
21	SM46G001	Aquia	Lexington Park Essex Dr	13.1	-450.8	-358.0
22	SM46G001	Upper Patapsco	Lexington Park Essex Dr	18.1	-569.2	-451.7
23	SM66G006	Aquia	Charlotte Hall	32.0	-249.2	-193.0
24	SM67G003	Aquia	Leonardtown	13.8	-343.0	-271.6
25	SM67G003	Upper Patapsco	Leonardtown	18.4	-543.6	-431.2
26	SM76G004	Piney Point	Town Creek	15.8	-168.5	-131.6
27	SM98G021	Upper Patapsco	Lexington Park First Colony	18.2	-568.9	-451.5
28	Hypothetical major user	Upper Patapsco	Elms Property	18.5	-586.0	-465.1
29	Hypothetical public supply	Upper Patapsco	Broad Creek	18.6	-578.5	-459.1
30	Hypothetical public supply	Upper Patapsco	Forrest Farms	18.3	-557.4	-442.3

[1]Map ID refers to locations shown in Figure 8.

Table 7b. Summary of future model simulations showing simulated heads at critical locations for 2030

Map ID[1]	Simulated head, in feet relative to sea level												
	Scenario number												
	0	1	2a	2b	3a	3b	4	5a	5b	6	7a	7b	8
Calvert County													
1	-163.2	-197.2	-216.7	-236.1	-177.7	-158.3	-188.0	-168.5	-139.8	-201.0	-198.3	-199.4	-201.9
2	-56.3	-72.0	-78.4	-84.7	-65.6	-59.2	-68.2	-84.4	-96.9	-80.0	-72.4	-72.8	-79.9
3	-83.3	-121.3	-134.3	-147.3	-108.4	-95.4	-96.1	-105.6	-89.8	-123.6	-121.5	-121.6	-123.2
4	-161.2	-200.0	-219.7	-239.5	-180.2	-160.4	-182.2	-172.8	-145.6	-204.0	-201.7	-203.3	-205.3
5	-58.6	-74.9	-81.6	-88.3	-68.2	-61.5	-71.1	-87.7	-100.6	-84.8	-75.4	-75.8	-83.6
6	-48.5	-74.9	-83.3	-91.7	-66.4	-58.0	-67.0	-68.1	-61.4	-76.7	-74.9	-75.0	-76.4
7	-45.2	-63.9	-69.5	-75.1	-58.3	-52.7	-57.6	-73.6	-83.3	-72.6	-63.9	-64.0	-113.0
8	-48.9	-66.9	-73.0	-79.0	-60.8	-54.8	-62.2	-75.7	-84.5	-93.4	-67.0	-67.2	-72.5
9	-59.0	-75.6	-82.4	-89.2	-68.9	-62.1	-71.8	-87.9	-100.3	-89.7	-76.1	-76.6	-84.1
Charles County													
10	-130.7	-194.8	-214.9	-235.0	-174.7	-154.6	-197.8	-207.3	-219.9	-205.9	-194.8	-194.8	-204.8
11	-195.3	-291.5	-321.2	-350.9	-261.8	-232.0	-284.9	-320.7	-350.0	-316.4	-291.5	-291.5	-317.3
12	-105.9	-215.7	-242.7	-269.6	-188.8	-161.9	-117.4	-163.7	-111.7	-217.0	-215.8	-215.8	-216.8
13	-140.6	-166.4	-183.9	-201.4	-148.9	-131.4	-216.2	-172.5	-178.5	-171.7	-166.4	-166.4	-171.0
14	-190.0	-313.8	-345.9	-378.0	-281.7	-249.6	-267.6	-366.4	-419.0	-352.9	-313.8	-313.9	-343.6
15	-165.7	-267.2	-295.0	-322.8	-239.4	-211.5	-255.7	-290.7	-314.3	-287.4	-267.2	-267.2	-283.7
16	-145.9	-234.3	-258.2	-282.1	-210.4	-186.5	-210.6	-271.5	-308.6	-267.1	-234.4	-234.4	-310.0
17	-127.9	-210.6	-232.5	-254.4	-188.8	-166.9	-179.0	-257.0	-303.4	-274.4	-210.7	-210.7	-235.5
18	-148.2	-242.7	-267.6	-292.6	-217.7	-192.8	-210.8	-292.5	-342.3	-309.5	-242.7	-242.7	-273.2
St. Mary's County													
19	-188.4	-247.6	-272.2	-296.7	-223.1	-198.5	-202.6	-209.6	-171.6	-251.3	-250.3	-253.0	-253.7
20	-59.2	-75.5	-82.3	-89.0	-68.8	-62.1	-72.5	-94.1	-112.8	-83.1	-76.1	-76.6	-86.3
21	-183.7	-240.5	-264.3	-288.1	-216.7	-192.9	-198.3	-204.4	-168.3	-244.1	-243.4	-246.2	-247.0
22	-58.4	-74.2	-80.8	-87.3	-67.6	-61.1	-71.0	-91.9	-109.6	-81.1	-74.7	-75.3	-86.0
23	-71.1	-122.0	-136.5	-151.1	-107.4	-92.9	-104.2	-109.7	-97.5	-124.0	-122.1	-122.2	-123.7
24	-91.4	-127.6	-140.5	-153.5	-114.6	-101.6	-112.9	-111.7	-95.8	-130.2	-128.1	-128.5	-130.5
25	-52.5	-68.8	-74.9	-81.1	-62.6	-56.4	-65.7	-82.4	-96.0	-76.3	-69.0	-69.3	-74.9
26	-37.1	-57.6	-64.7	-71.7	-50.5	-43.5	-55.1	-56.2	-54.8	-57.9	-57.7	-57.7	-58.0
27	-62.9	-81.5	-88.9	-96.2	-74.2	-66.8	-76.7	-96.3	-111.1	-90.3	-82.0	-82.4	-90.2
28	-48.5	-59.9	-64.8	-69.8	-55.0	-50.0	-57.0	-65.6	-71.3	-63.9	-60.4	-60.8	-125.6
29	-57.0	-74.4	-81.1	-87.8	-67.7	-61.0	-70.6	-85.5	-96.5	-86.0	-74.8	-75.1	-81.6
30	-56.0	-73.0	-79.5	-86.1	-66.4	-59.9	-70.0	-84.7	-96.4	-84.2	-73.3	-73.7	-80.1

Values in light gray exceed the management level
Values in dark gray exceed the aquifer top
[1]Map ID refers to locations shown in figure 8.

Table 7c. Summary of future model simulations showing remaining available drawdown at critical locations for 2030

Map ID[1]	Remaining available drawdown, in feet												
	Scenario number												
	0	1	2a	2b	3a	3b	4	5a	5b	6	7a	7b	8
Calvert County													
1	199.9	165.8	146.4	126.9	185.3	204.8	175.1	194.5	223.2	162.1	164.7	163.7	161.2
2	440.3	424.7	418.3	411.9	431.1	437.5	428.5	412.2	399.7	416.6	424.2	423.8	416.7
3	179.2	141.2	128.2	115.2	154.2	167.2	166.4	157.0	172.7	139.0	141.1	141.0	139.4
4	197.6	158.8	139.1	119.3	178.6	198.4	176.6	186.0	213.2	154.8	157.1	155.5	153.5
5	414.2	397.9	391.2	384.5	404.6	411.2	401.7	385.0	372.2	387.9	397.4	396.9	389.1
6	181.3	154.9	146.5	138.1	163.4	171.8	162.8	161.7	168.4	153.1	154.9	154.8	153.4
7	883.4	864.7	859.1	853.5	870.3	875.9	871.0	855.0	845.3	856.0	864.7	864.6	815.6
8	488.3	470.2	464.2	458.1	476.3	482.4	474.9	461.5	452.7	443.7	470.1	470.0	464.6
9	412.6	395.9	389.1	382.4	402.7	409.5	399.8	383.6	371.3	381.9	395.5	395.0	387.4
Charles County													
10	73.9	9.8	-10.3	-30.4	29.9	50.1	6.8	-2.7	-15.3	-1.3	9.8	9.8	-0.2
11	378.5	282.3	252.6	222.9	312.0	341.7	288.9	253.1	223.8	257.4	282.3	282.3	256.5
12	71.0	-38.8	-65.7	-92.7	-11.9	15.1	59.5	13.2	65.2	-40.1	-38.8	-38.9	-39.9
13	-11.6	-37.4	-54.9	-72.4	-19.9	-2.4	-87.2	-43.4	-49.5	-42.7	-37.4	-37.4	-42.0
14	404.4	280.6	248.5	216.4	312.7	344.8	326.8	228.0	175.4	241.5	280.5	280.5	250.7
15	234.3	132.8	105.0	77.2	160.7	188.5	144.3	109.3	85.7	112.7	132.8	132.8	116.3
16	547.1	458.7	434.8	410.9	482.6	506.5	482.4	421.5	384.4	425.9	458.7	458.6	383.0
17	507.5	424.8	402.9	381.1	446.7	468.5	456.5	378.4	332.1	361.0	424.8	424.8	399.9
18	493.7	399.3	374.3	349.3	424.2	449.1	431.1	349.4	299.6	332.4	399.2	399.2	368.7
St. Mary's County													
19	168.2	109.0	84.5	59.9	133.5	158.1	154.0	147.0	185.0	105.4	106.3	103.6	102.9
20	394.7	378.4	371.7	365.0	385.1	391.8	381.5	359.8	341.2	370.8	377.9	377.4	367.7
21	174.3	117.5	93.7	69.9	141.3	165.1	159.7	153.6	189.8	114.0	114.6	111.8	111.0
22	393.3	377.5	371.0	364.4	384.1	390.6	380.7	359.8	342.1	370.6	377.0	376.5	365.7
23	121.9	71.0	56.5	41.9	85.6	100.1	88.8	83.3	95.5	68.9	70.9	70.8	69.3
24	180.2	144.1	131.1	118.1	157.0	170.0	158.7	160.0	175.9	141.4	143.6	143.1	141.2
25	378.7	362.5	356.3	350.1	368.6	374.8	365.5	348.8	335.2	354.9	362.2	361.9	356.3
26	94.5	74.0	66.9	59.9	81.1	88.2	76.5	75.4	76.8	73.7	73.9	73.9	73.6
27	388.6	370.0	362.6	355.3	377.4	384.7	374.8	355.2	340.4	361.2	369.5	369.1	361.3
28	416.6	405.2	400.2	395.3	410.1	415.1	408.1	399.5	393.8	401.2	404.7	404.3	339.5
29	402.0	384.7	377.9	371.2	391.4	398.1	388.4	373.6	362.5	373.0	384.3	383.9	377.5
30	386.2	369.3	362.7	356.2	375.8	382.4	372.3	357.6	345.9	358.1	368.9	368.6	362.1

Values in light gray exceed the management level
Values in dark gray exceed the aquifer top
[1]Map ID refers to locations shown in figure 8.

Table 8. Mean error and root-mean-square for the flow-model calibration

[ME, mean error; RMS, root-mean-square]

	Stress period									
	1		2		3		4		5	
Aquifer	ME	RMS	ME	RMS	ME	RMS	ME	RMS	ME	RMS
Piney Point	0.7	4.0	-3.8	17.9	-4.5	10.8	-2.9	9.4	1.9	12.0
Aquia	3.8	6.5	-16.5	24.4	-9.6	14.1	-0.6	7.5	2.7	9.1
Magothy	0.5	10.9	7.4	7.4	1.3	9.9	3.2	9.0	1.2	7.5
Upper Patapsco	0.5	8.1	*	*	3.2	16.6	-5.2	15.4	-1.0	10.5
Lower Patapsco	6.8	6.8	6.3	12.6	6.5	11.8	-9.7	22.2	-3.4	16.7
All Aquifers	2.6	6.3	-11.9	22.3	-2.0	12.6	-1.8	13.1	0.5	11.0

* no water-level measurements available